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Stock Assessment of North Pacific Swordfish (*Xiphias gladius*) in 2009

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ABSTRACT

A stock assessment of North Pacific swordfish conducted in 2009 by the Billfish Working Group of the International Scientific Committee for Tuna and Tuna-like Species in the North Pacific Ocean (ISC) is described. Bayesian surplus production models were applied to assess the status of the North Pacific swordfish population under two alternative scenarios for stock structure. These were: (1) a two-stock scenario with stocks in the western and central Pacific (subarea 1) and in the eastern Pacific (subarea 2) and (2) a single scenario stock covering the North Pacific. Of these scenarios, the two-stock scenario was considered the most plausible based on analyses of patterns in Japanese longline catch-per-unit effort (CPUE) and differences in life history characteristics among swordfish in the western and central and eastern Pacific regions. Biomass production was modeled using a 3-parameter production model that allowed production to vary from a symmetric Schaefer curve. Input fishery data included nominal landings of North Pacific swordfish during 1951–2006. Potential relative abundance indices for swordfish consisted of standardized CPUE for Japanese, Chinese-Taipei, and U.S. longline fisheries and the California gillnet fishery for each stock structure scenario. Lognormal prior distributions for intrinsic growth rate and carrying capacity were assumed to be moderately precise with coefficients of variation set at 50%. Goodness-of-fit diagnostics for comparing the fits of alternative model configurations included the root-mean squared error of CPUE fits and the standardized CPUE residuals. Production model results indicated that the Japanese longline CPUE were the most influential relative abundance indices for each stock scenario. Model results also indicated that assumptions about the prior means for intrinsic growth rate and carrying capacity may also be important depending on the model assumptions.

In what follows, model structure, data inputs, and output results are described in detail including goodness-of-fit diagnostics, biomass and harvest rate trends. Stock projections that were conducted for the two-stock scenario are also described. The practical benefits of applying a Bayesian estimation framework to assess the biological status of the North Pacific swordfish resource are also discussed. Overall, these results represented the Billfish Working Group (WG) consensus on model structure, data inputs, and output results for the North Pacific swordfish stock assessment conducted in 2009 (ISC Billfish WG, 2009).

INTRODUCTION

Swordfish (*Xiphias gladius*), *a.k.a.* broadbill swordfish, inhabit a wide region of the Pacific between the latitudes of 50˚ N and 50˚ S (Ward et al., 2000). Swordfish is a highly migratory species with high economic value in both commercial and recreational fisheries. In the North Pacific, the annual total catch has fluctuated around 15,000 mt since 2001. The majority of catch has been taken by longline fishing vessels from Japan, Chinese-Taipei and the U.S. (Fig. 1), which accounted for 95% of the total harvest in the North Pacific in 2005, with the remaining catch taken by Korea and Mexico. There is potential interest in increasing the harvest of North Pacific swordfish and this would require an appropriate stock assessment, management for conservation, and the sustainable development of the fishery.

Stock assessments on the North Pacific swordfish have been conducted primarily using catch and the abundance indices (i.e., catch-per-unit effort: CPUE). Kleiber and Yokawa (2004) used MULTIFAN-CL to conduct a preliminary North Pacific swordfish in a four-region model. In two subsequent studies, Wang et al. (2005; 2007) applied a similar length-structured modeling approach which included some sex-specific data. These three studies concluded that there was limited contrast in the North Pacific swordfish fishery CPUE data to estimate stock status relative to biological reference points using highly parameterized age- or length-structured modeling approaches. Updated catch and effort data and the use of a production modeling approach with fewer parameters to estimate, however, might be expected to improve model fits to CPUE and to help estimate recent trends in swordfish abundance and harvest rates.

This assessment applied a Bayesian statistical framework to estimate parameters of production models to assess the North Pacific swordfish population using updated catch and effort through 2006. The use of a Bayesian approach provided direct estimates of parameter uncertainty that are straightforward to interpret and are appropriate for risk analysis. The production models included both process error for biomass production dynamics and allowed for heterogeneous observation errors for fitting the observed CPUE data from multiple fishing fleets. Production models were formulated for the two-stock structure scenarios, e.g., the two-stock scenario with western and eastern subareas and the single-stock scenario. The overall goal was to assess swordfish stock status under alternative stock structure scenarios using Bayesian production models that could incorporate multiple abundance indices and heterogeneous observation errors.

MATERIALS

Data

Fishery catch data for assessing North Pacific swordfish were taken from the most recent summary of available fishery-dependent data (Courtney and Wagatsuma, 2009). Commercial catch biomass data for Japanese, Chinese-Taipei, and Hawaii (U.S.) longline fisheries were available for 1951–2006 under each stock structure scenario (Fig. 1) with Japanese vessels producing the majority of landings. The catch data were aggregated by region under the two–stock structure scenarios supported by the ISC Billfish Working Group. The two-stock scenario assumed that two stocks existed and were separated by a diagonal boundary extending from Baja, California, to the Equator (Fig. 2a), based on the analysis by Ichinokawa and Brodziak (2008). The single-stock scenario assumed that there was one unit stock of swordfish north of the equator (Fig. 2b). Overall, the catch data were used to model the effects of fishery removals from the North Pacific swordfish population during 1951–2006.

Estimates of standardized commercial fishery CPUE were also collected from Courtney and Wagatsuma (2009) for each stock scenario. Under the two-stock scenario, the set of available standardized CPUE time series was different for each subarea. The standardized CPUE time series for subarea 1 in the western central Pacific included Japanese longline CPUE (1952–2006, n = 55), Chinese-Taipei longline CPUE (1995–2006, n = 12), and Hawaii shallow-set longline CPUE (Index 1, 1995–2000 and Index 2, 2004–2006, n = 9). Due to changes in the fishery regulations for the shallow-set fishery, the time series of Hawaii shallow-set data was treated as two separate indices of relative abundance indices with index 1 for 1995–2000 and with index 2 for 2004–2006. The standardized CPUE time series for subarea 2 in the eastern Pacific included Japanese longline CPUE (1955–2006, n = 52) and Taiwanese longline CPUE (1995–2006, n = 12). The observed time series of standardized CPUE were used to model changes in the relative abundance of swordfish through time. The standardized CPUE time series for the single-stock scenario included Japanese longline CPUE (1952–2006, n = 55), Chinese-Taipei longline CPUE (1995–2006, n = 12), and Hawaii shallow-set longline CPUE (Index 1, 1995–2000 and Index 2, 2004–2006, n = 9). Overall, there were four relative abundance indices for subarea 1 under the two-stock scenario and the North Pacific under the single-stock scenario, while there were two relative abundance indices for subarea 2 under the two-stock scenario.

METHODS

Production Model

Swordfish production models were formulated as Bayesian-state space models with explicit observation and process error terms (e.g., Meyer and Millar, 1999; Brodziak, 2007). The biomass time series comprised the unobserved state variables which were estimated from the observed relative abundance indices (i.e., CPUE) and catches using observation error likelihood function and prior distributions for model parameters (θ). In this case, the observation error likelihood measured the discrepancy between observed and predicted CPUE, and the prior distributions represented the relative degree of belief about the possible values of model parameters.

The process dynamics represented the fluctuations in exploitable swordfish biomass due to density-dependent processes and fishery harvests. The production dynamics of biomass were based on a power function model with an annual time step. Under this three-parameter model, current biomass (B_T) depended on the previous biomass (B_{T-1}), catch (C_{T-1}), intrinsic growth rate (R), carrying capacity (K), and a production shape parameter (S) for $T = 2,\ldots, N$.

(1) $$B_T = B_{T-1} + R \cdot B_{T-1}\left(1-\left(\frac{B_{T-1}}{K}\right)^S\right) - C_{T-1}$$

The production model shape parameter, *S,* determined where surplus production peaked as biomass varied as a fraction of carrying capacity. If the shape parameter was less than unity ($0 < S < 1$), then surplus production peaked when biomass was below ½ of *K* (i.e., a right-skewed production curve). If the shape parameter was greater than unity ($S > 1$), then biomass production was highest when biomass was above ½ of *K* (i.e., a left-skewed production curve). If the shape parameter was identically unity ($S = 1$), then the production model was identical to a discrete-time Schaefer production model where maximum surplus production occurred when biomass was equal to ½ of *S*. Thus, the shape of the biomass production curve could be symmetric, right- or left-skewed depending on the estimated value of S.

The power function model was reparameterized using the proportion of carrying capacity ($P = B/K$) to improve the efficiency of the Markov Chain Monte Carlo algorithm used to estimate parameters (i.e., Meyer and Millar, 1999). Given this parameterization, the process dynamics for the power function model were

(2) $$P_T = P_{T-1} + R \cdot P_{T-1}\left(1 - P_{T-1}^S\right) - \frac{C_{T-1}}{K}$$

Biological Reference Points

The values of biomass and harvest rate that maximize biomass production were relevant as biological reference points for maximum sustainable yield (MSY). For the discrete-time power function model, the biomass that produced MSY (B_{MSY}) was

(3) $$B_{MSY} = K \cdot (S+1)^{\frac{-1}{S}}$$

The corresponding harvest rate that produced MSY (H_{MSY}) was

(4) $$H_{MSY} = R\left(1 - \frac{1}{S+1}\right)$$

and the associated value of maximum sustainable yield (MSY) was

(5) $$MSY = R\left(1 - \frac{1}{S+1}\right) \cdot K\left(S+1\right)^{\frac{-1}{S}}$$

Thus, the production model produced direct estimates of biological reference points for swordfish that are commonly used for determining stock status.

Observation Error Model

The observation error model related the observed fishery CPUE to the exploitable biomass of the swordfish stock under each scenario. It was assumed that each CPUE index (*I*) is proportional to biomass with catchability coefficient *Q*

(6) $$I_T = QB_T = QKP_T$$

The observed CPUE values were subject to natural sampling variation which was assumed to be lognormally distributed. In preliminary model formulations, the WG explored models with weighted lognormal observation errors using annual estimates of the coefficient of variation of standardized CPUE indices (e.g., Maunder and Starr, 2003). However, unweighted observation errors were used in the final model formulation because of uncertainty about the reliability of variance estimates of annual CPUE indices (ISC Billfish WG, 2009). The observation errors were distributed as $\nu_T = e^{V_T}$ where the V_T are independent and identically distributed normal random variables with zero mean and variance τ^2.

Given the lognormal observation errors, the observation equations for each annual period indexed by $T = 1,\ldots, N$ were

(7) $$I_T = QKP_T \cdot \nu_T$$

This specified the general form of the observation error likelihood function $p(I_T|\theta)$ for each fishing fleet through time.

Process Error Model

The process error model compared the dynamics of exploitable biomass to natural variability in demographic and environmental processes affecting the swordfish stock. The deterministic process dynamics (Equation 2) were subject to natural variation as a result of fluctuations in life history parameters, trophic interactions, environmental conditions and other factors. In this case, the process error represented the joint effects of a large number of random multiplicative events which combined to form a multiplicative lognormal process under the Central Limit Theorem. As a result, the process error terms were assumed to be independent and lognormally distributed random variables $\eta_T = e^{U_T}$ where the U_T were normal random variables with mean 0 and variance σ^2.

Given the process errors, the state equations defined the stochastic process dynamics by relating the unobserved biomass states to the observed catches and the estimated population dynamics parameters. Assuming multiplicative lognormal process errors, the state equations for the initial time period ($T = 1$) and subsequent periods ($T > 1$) were

(8)
$$\begin{aligned} P_1 &= \eta_1 \\ P_T &= \left(P_{T-1} + R \cdot P_{T-1}\left(1 - P_{T-1}^S\right) - \frac{C_{T-1}}{K} \right) \cdot \eta_T \quad for\ T > 1 \end{aligned}$$

These coupled state equations set the conditional prior distribution for the proportion of carrying capacity, $p(P_T)$, in each time period T, conditioned on the proportion in the previous period.

Prior Distributions

Under the Bayesian paradigm, prior distributions are employed to quantify existing knowledge, or the lack thereof, of the likely value of each model parameter. For the production model, the model parameters consisted of the carrying capacity, the intrinsic growth rate, the shape parameter, the catchability coefficients, the process and observation error variances, and the annual biomasses as a proportion of carrying capacity. Auxiliary information was incorporated into the formulation of the prior distributions when it was available.

Prior for Carrying Capacity

The prior distribution for the carrying capacity $p(K)$ was a lognormal distribution with mean $\left(\mu_K\right)$ and variance $\left(\sigma_K^2\right)$ parameters.

(9)
$$p(K) = \frac{1}{\sqrt{2\pi} K \sigma_K} \exp\left(-\frac{\left(\log K - \mu_K\right)^2}{2\sigma_K^2} \right)$$

The variance parameter was set to achieve a coefficient of variation (CV) for K of 50%, e.g., $CV[K] = \left(\exp\left(\sigma_K^2\right) - 1\right)^{\frac{1}{2}} = 0.5$. For the two-stock scenario, the mean K for subarea 1 was set at 150,000 mt while the mean K for subarea 2 was set at 75,000 mt. The mean K parameter was set at 150,000 mt under the single-stock scenario. These mean values were chosen to reflect the magnitude of exploitable biomass likely needed to support the observed fishery catches under each scenario.

Prior for Intrinsic Growth Rate

The prior distribution for intrinsic growth rate $p(R)$ was a lognormal distribution with mean $\left(\mu_R\right)$ and variance $\left(\sigma_R^2\right)$ parameters set to achieve a CV for R of 50%

(10) $$p(R) = \frac{1}{\sqrt{2\pi}R\sigma_R}\exp\left(-\frac{\left(\log R-\mu_R\right)^2}{2\sigma_R^2}\right)$$

The mean R parameter was set to be $\mu_R = 0.5$ for each stock scenario. This mean value was slightly higher than the range of prior means of (0.40, 0.43) estimated for North and South Atlantic swordfish, respectively, based on an analysis of life history parameters (McAllister et al., 2000). A similar analysis using life history parameters for North Pacific swordfish and the mean generation time approach (see McAllister et al., 2001) suggested higher mean values of R of approximately 0.9 to 1.0 were appropriate. This analysis assumed female growth and maturation from DeMartini et al. (2000) and DeMartini et al. (2007) and used five alternative natural mortality rate estimators (Hoenig, Alverson and Carney, Pauly, Beverton-Holt 2nd invariant, and Lorenzen Tropical) from Brodziak (2009) to calculate five alternative estimates of R. The primary difference between the Atlantic and Pacific swordfish life history parameters was the value of natural mortality. McAllister et al. (2000) assumed a constant natural mortality rate of M = 0.2 for Atlantic swordfish, while the Pacific swordfish natural mortality rate was estimated to be M ≈ 0.35, roughly 75% higher than the Atlantic swordfish value. While there was uncertainty about an appropriate prior mean for R, setting the prior mean to be $\mu_R = 0.5$ with a CV of 50% allowed sufficient flexibility to estimate the probable value of R given the observed catch and CPUE data.

Prior for Production Shape Parameter

The prior distribution for the production function shape parameter $p(S)$ was a gamma distribution with scale parameter λ and shape parameter k:

(11) $$p(S) = \frac{\lambda^k S^{k-1}\exp\left(-\lambda S\right)}{\Gamma\left(k\right)}$$

The values of the scale and shape parameters were set to $\lambda = k = 2$. This choice of parameters set the mean of $p(S)$ to be $\mu_S = 1$, which corresponded to the value of S for the Schaefer production model. This choice also implied that the CV of the shape parameter prior was 71%. In effect, the shape parameter prior was centered on the symmetric Schaefer model as the default with sufficient flexibility to estimate a nonsymmetrical production function if needed.

Prior for Catchability

The prior for the catchability coefficient $p(Q)$ was chosen to be a diffuse inverse-gamma distribution with scale parameter λ and shape parameter k.

$$\textbf{(12)} \qquad p(Q) = \frac{\lambda^k Q^{-(k+1)}}{\Gamma(k)} \exp\left(\frac{-\lambda}{Q}\right)$$

The scale and shape parameters were set to be $\lambda = k = 0.001$. This choice of parameters implied that $1/Q$ has a mean of 1 and a variance of 1000 and produced a relatively uninformative prior. Since $1/Q$ is unbounded at $Q = 0$, an additional numerical constraint that Q be no smaller than 0.0001 was imposed for the Markov Chain Monte Carlo (MCMC) sampling.

Priors for Error Variances

Priors for the process error variance $p(\sigma^2)$ and observation error variance $p(\tau^2)$ were chosen to be inverse-gamma distributions. The choice of an inverse gamma distribution implied that the associated prior for error precision ($\pi = 1/\sigma^2$) was effectively $p(\pi) \propto \pi^{-1}$ which is the Jeffrey's prior for the precision parameter (Congdon, 2001). As a result, inferences based on the gamma assumption were scale invariant and were not affected by changing the scale of the variance parameter. For the process error variance prior, the scale parameter was set to $\lambda = 4$ and the shape parameter was $k = 0.1$. This choice of parameters produced an expected value of approximately $E[\sigma^2] = 0.025$ with a CV of 16%. Similarly, for the observation error variance prior, the scale parameter was set to $\lambda = 2$ and the shape parameter was $k = 0.1$. This choice of parameters produced an expected value of approximately $E[\tau^2] = 0.223$ with a CV of 50%. Given these prior assumptions, the initial observation error variance was roughly threefold greater than the process error variance. Of course, the posterior means of the process and observation errors estimated from the MCMC sampling also depended on the model fits to the observed data.

Priors for Proportions of Carrying Capacity

Prior distributions for the time series of the proportion of biomass to carrying capacity, $p(P_T)$, were lognormal distributions as specified in the process dynamics. The mean proportion of carrying capacity for the initial year of 1951 was set to 0.9 under each stock-structure scenario. This corresponded to an assumption that the North Pacific swordfish population was lightly exploited and had biomass near its carrying capacity following a period of limited directed fishing during World War II.

Posterior Distribution

The joint posterior distribution of the swordfish production model needs to be sampled to make inferences about estimates of the model parameters. Given the catch and the CPUE data *D*, the posterior distribution $p(\theta|D)$ was proportional to the product of the prior distributions and the likelihood of the CPUE data via Bayes' theorem

(13) $$p(\theta \mid D) \propto p(K)\,p(R)\,p(S)\,p(Q)\,p(\sigma^2)\,p(\tau^2)\prod_{T=1}^{N} p(P_T)\prod_{T=1}^{N} p(I_T \mid \theta)$$

Parameter estimation for this nonlinear multiparameter model was based on generating a large number of independent samples from the posterior distribution. In this case, the Markov Chain Monte Carlo (MCMC) simulation using Gibbs sampling was applied to numerically generate a sequence of samples from the posterior distribution (Gilks et al., 1996). The WINBUGS software (Spiegelhalter et al., 2003) was used to set the initial conditions, perform the MCMC calculations, and summarize the results.

Markov Chain Monte Carlo simulations were conducted in an identical manner for each of the swordfish stock-structure scenario models described below. Three chains of 60,000 samples were simulated for each model. A burn-in period of 10,000 samples were removed from each chain to remove any dependence of the MCMC samples on the initial conditions. Next, each chain was thinned by 2 to reduce autocorrelation, and every other sample was used for inference. As a result, 75,000 samples from the posterior were used for summarizing model results. Convergence of the MCMC simulations to the posterior distribution was checked using the Gelman and Rubin diagnostic (Gelman and Rubin, 1992) and the Heidelberger and Welch stationarity test (Heidelberger and Welch, 1992) as implemented in the R Language (R Development Core Team, 2009) using the CODA software package (Best et al., 1996; Plummer et al., 2006). These convergence diagnostics were monitored for several key model parameters (intrinsic growth rate, carrying capacity, production function shape parameter, and catchability coefficients) to verify convergence of the MCMC chains to the posterior distribution. In addition, Monte Carlo errors, which measured the variation of the mean of each parameter based on the MCMC simulation, were calculated and compared to the posterior standard deviation of the key model parameters. In this case, relatively small Monte Carlo errors on the order of a few percent of the posterior standard deviation provided an empirical check that parameter variability due to the MCMC simulations was low (e.g., Ntzoufras, 2009).

Goodness-of-Fit Criteria

Model residuals were used to measure the goodness of fit of the alternative production models. Residuals for the CPUE series are the log-scale observation errors ε_T.

(14) $$\varepsilon_T = \ln(I_T) - \ln(QKP_T)$$

Nonrandom patterns in the residuals indicated that the observed CPUE did not conform to one or more model assumptions. The root mean-squared error (RMSE) of the CPUE fit provided another diagnostic of the model goodness of fit with lower RMSE indicating a better fit when comparing models with the same number of parameters.

Two-stock Scenario Projections at Recent Average Fishing Mortality

Stochastic projections were conducted to illustrate the possible changes in exploitable biomass and catch if the swordfish fishing effort was similar to the recent average effort pattern. These projections estimated the potential distributions of exploitable biomass and catch biomass under the two-stock scenario, which was considered to be the most plausible stock structure scenario by the WG, incorporating the estimated joint posterior distribution of model parameters. These projections assumed status quo fishing effort for swordfish would continue in subareas 1 and 2 during 2007–2010. Stochastic harvest rates were simulated to project likely distributions of exploitable swordfish biomass and catch in each subarea. The stochastic harvest rates were assumed to be random independent and identically distributed samples from a normal distribution with a mean equal to the 2004–2006 3-year average harvest rate and variance equal to the observed variability in mean harvest rate during 2004–2006 by subarea. The initial conditions for the projections were based on the MCMC samples from the estimated posterior distribution of exploitable swordfish biomass by subarea in 2006.

RESULTS

Convergence to Posterior Distribution

The Gelman and Rubin (1992) potential scale-reduction factor was calculated for the intrinsic growth rate, carrying capacity, production function shape parameter, and catchability coefficients under each stock structure scenario. For all of these key parameters, the estimated reduction factors were equal to 1.00, which was consistent with the convergence in distribution of the MCMC samples to the joint posterior distribution. Similarly, the Heidelberger and Welch stationarity test could not reject the hypothesis that the MCMC chains were stationary at the 5% confidence level for any of the parameters, with the exception of the shape parameter S under the subarea 2 model. Empirical examination of the Monte Carlo errors, a measure of the variability in each estimate based on simulation, indicated that these errors were relatively small, ranging from 0.6% to 2.5% of the estimated posterior standard deviation for the key parameters. This was also consistent with convergence of the MCMC chains to the posterior distributions. Last, visual inspection of density plots of the posterior distributions of the intrinsic growth rate, carrying capacity, production function shape parameter, and catchability coefficients indicated that these densities were smooth and unimodal for all parameters as expected for a convergent sequence of MCMC samples. Overall, the convergence diagnostics that were examined indicated that the MCMC samples generated from the production model had numerically converged to the posterior distribution.

Two-stock Scenario Model Fits to CPUE

For subarea 1 under the two-stock scenario, results of the fits to standardized CPUE indicated that the Japanese longline CPUE had the lowest RMSE, while the Hawaii shallow-set longline CPUE had the highest RMSE (Table 1). Predicted Japanese CPUE fluctuated around the observed CPUE time series (Fig. 3.1). The log-scale residuals had no time trend ($P = 0.35$), were normally distributed ($P = 0.22$), and had constant variance ($P = 0.70$). The Taiwanese longline CPUE fit had a pattern of consecutive negative residuals in the late 1990s (Fig. 3.2). There was a detectable time trend in the residuals ($P = 0.05$), and the log-scale residuals were normally distributed ($P = 0.21$) and had constant variance ($P = 0.15$). Fits to the Hawaii shallow-set longline CPUE appeared to have an increasing trend in residuals (Fig. 3.3). There was a significant increasing trend during 1995–2000 ($P = 0.02$) and during 2004–2006 ($P = 0.02$). The log-scale residuals were normally distributed during 1995–2000 ($P = 0.48$) but were not normally distributed during 2004–2006 ($P < 0.01$). The log-scale residuals did not have constant variance during 1995–2000 ($P = 0.04$) or during 2004–2006 ($P < 0.01$). Overall, some of the fits to the CPUE time series in subarea 1 appeared nonrandom and in particular, the Taiwanese and Hawaii shallow-set long CPUE fits exhibited increasing trends in their residual patterns.

For subarea 2 under the two-stock scenario, the model fits to standardized CPUE indicated that the Japanese longline CPUE had a lower RMSE than the fit to the Taiwanese CPUE (Table 1). The fit to the Japanese longline CPUE (Fig. 4.1) exhibited some large negative residuals in the 1950s but otherwise appeared to fluctuate randomly about the observed CPUE. The residuals had no time trend ($P = 0.24$), but the log-scale residuals were not normally distributed ($P < 0.01$) and the variance was not constant ($P = 0.04$). In contrast, there was no apparent pattern in the fit to the Taiwanese longline CPUE (Fig. 4.2). In this case, the residuals had no detectable trend ($P = 0.72$), the log-scale residuals were normally distributed ($P = 0.89$), but the variance was not constant ($P = 0.03$). Overall, in subarea 2 there was a good fit to the Taiwanese longline CPUE and some lack of fit to the Japanese longline CPUE in the 1950s.

Single-stock Scenario Model Fits to CPUE

Results of the fits to standardized CPUE under the single-stock scenario indicated that the Japanese longline CPUE had the lowest RMSE, while the Hawaii shallow-set longline CPUE had the poorest fit (Table 1). Predicted Japanese CPUE appeared to randomly fluctuate about the observed CPUE time series (Fig. 5.1). Examination of the log-scale residuals indicated that there was a moderate but significant increasing trend with time ($P = 0.02$). The residuals were normally distributed ($P = 0.54$) and had constant variance ($P = 0.52$). The fit to the observed Taiwanese longline CPUE had a pattern of consecutive negative residuals that appeared nonrandom (Fig. 5.2). However, there was no significant trend in residuals ($P = 0.13$) and the log-scale residuals were normally distributed ($P = 0.16$) with constant variance ($P = 0.09$). Similarly, the fits to the Hawaii shallow-set longline CPUE had a negative then positive pattern of residuals (Fig. 5.3), but no trends in residuals were detected during 1995–2000 (P = 0.21) or during 2004–2006 (P = 0.23). The log-scale residuals were normally distributed during 1995–2000 (P = 0.48) with constant variance (P = 0.06) but were not normally distributed (P < 0.01) and showed constant variance (P < 0.01) during 2004–2006. Overall, under the single-stock scenario, the fits to the CPUE time series appeared adequate although there was a lack of conformance to model error assumptions in a few cases.

Posterior Estimates of Model Parameters and Reference Points

Estimates of production model parameters varied between the stock structure scenarios (Table 2). Under the single-stock scenario, the intrinsic growth rate was estimated to be R = 0.68. In contrast, under the two-stock scenario the estimates of R were 0.58 and 0.40 for subareas 1 and 2, or 15% and 41% below the single-stock estimate. The estimate of K under the single-stock scenario (K = 113.6 kt) was about 33% less than the sum of the estimates of K under the two-stock scenario ($K_1 + K_2$= 170.5 kt). The estimate of the production model shape parameter for the single-stock scenario was S = 1.25, indicating a left-skewed production curve. In comparison, the estimate of S_1 for subarea 1 was approximately 1.02, indicating a symmetric biomass production curve. The estimate of S_2 for subarea 2 was S_2 = 0.66, indicating a right-skewed production curve although this estimate of S_2 was imprecise with a CV of 81%. Overall, estimates of production model parameters R, K, and S differed between the stock structure scenarios.

Estimates of biological reference points also differed between the stock structure scenarios (Table 2). The mean estimate of B_{MSY} under the single-stock scenario was B_{MSY} = 58.4. This was about 29% below the sum of the estimates of B_{MSY} under the two-stock scenario. The mean estimate of H_{MSY} under the single-stock scenario was H_{MSY} = 0.34. In comparison, the estimates of H_{MSY} under the two-stock scenario were 0.26 and 0.13 for subareas 1 and 2, or 24% and 62% less than the single-stock estimate. In contrast, the mean estimate of MSY under the single-stock scenario was MSY = 19.1 kt which was only 9% higher than the sum of the MSY estimates under the two-stock scenario. Overall, the results indicated that the North Pacific swordfish population would be considered to be a smaller (lower carrying capacity) and more productive stock (higher intrinsic growth rate) under the single-stock scenario than as a combination of two stocks under the two-stock scenario.

In contrast to the estimates of production model parameters and biological reference points, there was no practical difference in the estimates of stock status in 2006 between the two stock scenarios (Table 2). In particular, the mean estimates of B_{2006} were greater than B_{MSY} under both stock scenarios and subareas, and the associated probabilities of B_{2006} exceeding B_{MSY} were 1 except for subarea 1 where that probability was 0.93. Similarly, mean estimates of exploitation rate in 2006 were below H_{MSY} for both stock scenarios and subareas and the corresponding probabilities that H_{2006} exceeded H_{MSY} were no greater than 0.01. This indicated that the choice of stock scenario had no practical impact on the status of the North Pacific swordfish population with respect to MSY-based reference points.

Posterior Estimates of Exploitable Biomass and Exploitation Rate

Exploitable biomass of the swordfish stock in subarea 1 under the two-stock scenario fluctuated above B_{MSY} for most of the assessment time horizon (Table 3.1, Fig. 6.1). Biomass increased during the 1980s and has since declined to roughly 25% above B_{MSY}. Exploitation rates in subarea 1 increased from low values in the 1950s to a peak of about 33% around 1960 and then declined to fluctuate about 50% of H_{MSY} from the mid 1960s to the late 1980s. Exploitation rates increased to fluctuate below H_{MSY} during the 1990s and then declined in the 2000s to about 67% of H_{MSY}. Overall, exploitable biomass in subarea 1 remained at or above B_{MSY}, while exploitation rates remained at or below H_{MSY} throughout the assessment time horizon.

Exploitable biomass in subarea 2 under the two-stock scenario fluctuated at or above B_{MSY} throughout the assessment time horizon (Table 3.2, Fig. 6.2). Biomass increased to a peak around 2000 and has since declined in the 2000s, albeit to twofold higher than B_{MSY}. Exploitation rates in subarea 2 remained at or below H_{MSY} throughout the assessment time horizon (Fig. 4.3). Overall, the stock in subarea 2 does not appear to have been depleted or experienced overfishing under this model scenario.

Under the single-stock scenario, exploitable biomass fluctuated above B_{MSY} during the 1950s to 2000s (Table 3.3, Fig. 6.3). Biomass increased in the late 1980s, subsequently declined in the late 1990s, and then increased in the 2000s. Exploitation rates were below H_{MSY} in the early 1950s, increased to a peak of about 33% around 1960, and subsequently declined to roughly 50% of H_{MSY} during 1965–1990 (Fig. 4.1). Exploitation rates increased in the early 1990s to fluctuate around 70% of H_{MSY} and subsequently declined in the early 2000s to roughly 50% of H_{MSY}. Under the single-stock scenario, exploitable biomass remained above B_{MSY}, and exploitation rates remained below H_{MSY} throughout the assessment time horizon.

Two-stock Scenario Projections at Recent Average Fishing Mortality

In subarea 1, swordfish exploitable biomass was projected to fluctuate around 77 kt during 2007–2010 if fishing effort remained stable (Fig. 5.1). The mean projected catch biomass in 2007 was 12.2 kt with a 95% CI of 7.2 to 19.3 kt. In comparison, the projected catch in 2010 averaged 12.2 kt with a 95% CI of 8.6 to 17.1 kt. Overall, the projections indicated that exploitable biomass and catch of swordfish in subarea 1 were likely sustainable if current levels of fishing effort were maintained during 2007–2010.

Projections for subarea 2 indicated that swordfish exploitable biomass would likely decline from 57 kt in 2007 to 51 kt in 2010, as the stock was fished down to slightly below its carrying capacity by 2010. The mean projected catch biomass of swordfish in subarea 1 in 2007 was 2.3 kt with a 95% CI of 1.0 to 4.6 kt. In comparison, the mean projected in 2010 was 2.0 kt with a 95% CI of 0.9 to 3.8 kt. Overall, the projections indicated that there would likely be a moderate decline in swordfish exploitable biomass and catch biomass in subarea 2 if current levels of fishing effort were maintained during 2007–2010. This decline was the result of high stock biomass in excess of carrying capacity in subarea 2 and the application of a relatively low annual harvest rate of 4% or roughly 0.3*F_{MSY}.

DISCUSSION

This study applied a Bayesian statistical framework to estimate parameters of production models to assess the North Pacific swordfish under two alternative stock-structure scenarios. Our results showed the dynamic changes in biomass and harvest rate that reflected variations in the catch and CPUE time series throughout the assessment horizon. Overall, the results indicated that the North Pacific swordfish population would be estimated to be a smaller (lower carrying capacity K) and more productive stock (higher intrinsic growth rate R) under the single-stock scenario than as a combination of two stocks under the two-stock scenario. Similar results were found for the estimated biological reference points under the two scenarios which indicated that the choice of stock scenario had no practical impact on the status of the North Pacific swordfish population with respect to MSY-based reference points. The MSY results from the two stock scenarios suggested that the North Pacific swordfish population was fairly resilient to fishing pressures and that current biomass was close to the level of B_{MSY}. As a result, the North Pacific swordfish population biomass was not below B_{MSY} in 2006 with a very high degree of confidence, i.e., at least a 9 out of 10 chance. Under both stock structure scenarios, swordfish exploitation rates were estimated to have remained below H_{MSY} throughout the assessment time horizon. In 2006, there was a very high degree of confidence that the swordfish population was not experiencing overfishing (i.e., $F_{2006} > F_{MSY}$). This implied that the current levels of fishing effort directed at swordfish in the North Pacific was likely sufficient to conserve the swordfish stocks (or stock) while providing for a sustainable fishery.

The benefits of applying a Bayesian estimation framework were considered to be important for effectively conveying stock assessment results to fisheries managers and stakeholders. Using a Bayesian estimation approach allowed one to make clear statements about the degree of confidence and uncertainty in estimated quantities (e.g., Ellison, 2004). In particular, the probabilistic interpretation of stock status showed that it was very likely (93% to 100% chance) that the swordfish population biomass was above B_{MSY}, and also extremely unlikely (0% to 1% chance) that the stock was being fished in excess of H_{MSY}, regardless of the stock-structure scenario. Similarly, the use of a Bayesian approach would be expected to help with the implementation of a precautionary approach to swordfish fishery management in which managers could choose acceptable risk levels for undesirable outcomes and apply decision tables to judge the efficacy of alternative management options (Hilborn and Peterman, 1996; McAllister and Kirkwood, 1998).

We concluded from the application of a Bayesian production model for the North Pacific swordfish that it was possible to produce parameter estimates and credibility intervals to measure changes in exploitable biomass and harvest rate through time. Although the results suggested that the North Pacific swordfish was not currently depleted, there are likely rising economic incentives for increasing swordfish harvest. Such incentives may lead to a decision to increase the future level of fishing effort on the population, and this could lead to unsustainable fisheries. In this context, our probabilistic results could be used to provide estimates of the potential fishing capacity for North Pacific swordfish along with an appropriate characterization of the uncertainty in these estimates using the approach of Arrizabalaga et al. (2009). While the short-term projections of fishery yield under status quo fishing effort suggested that the swordfish population and fisheries would likely be stable in the near term, we also recommend that further assessment work on North Pacific swordfish should be conducted using more detailed biological data with age- or length-structured models.

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Table 1.--Root mean-squared errors of model fits to CPUE time series under the single-stock and two-stock scenarios.

Stock Scenario	Japanese Longline	Taiwanese Longline	Hawaii Longline Shallow-Set 1	Hawaii Longline Shallow-Set 2
Single-Stock Scenario	0.153	0.291	0.219	0.225
Two-Stock Scenario Subarea 1	0.151	0.318	0.280	0.236
Two-Stock Scenario Subarea 2	0.228	0.295	-	-

Table 2.--Mean estimates of intrinsic growth rate (*R*), carrying capacity (*K*), production model shape parameter (*M*), biomass to produce maximum sustainable yield (B_{MSY}), exploitation rate to produce maximum sustainable yield (H_{MSY}), maximum sustainable yield (MSY), exploitable biomass in 2006 (B_{2006}), probability that B_{2006} exceeds B_{MSY}, exploitation rate in 2006, and probability that H_{2006} exceeds H_{MSY} under the single-stock and two-stock scenarios as well as estimated coefficient of variation (%) of model parameters in parentheses.

Stock Scenario	Mean *R*	Mean *K*	Mean *M*	Mean B_{MSY}	Mean H_{MSY}	Mean MSY	Mean B_{2006}	$Pr(B_{2006}>B_{MSY})$	Mean H_{2006}	$Pr(H_{2006}>H_{MSY})$
Single-stock Scenario	0.68 (36%)	113.6 (23%)	1.25 (44%)	58.4 (22%)	0.34 (25%)	19.1 (16%)	98.0 (27%)	1.00	0.13 (27%)	0.00
Two-stock Scenario Subarea 1	0.58 (38%)	115.9 (21%)	1.02 (47%)	57.3 (21%)	0.26 (24%)	14.4 (14%)	74.9 (26%)	0.93	0.14 (26%)	0.00
Two-stock Scenario Subarea 2	0.40 (45%)	54.6 (28%)	0.66 (81%)	24.8 (28%)	0.13 (38%)	3.1 (45%)	59.7 (36%)	1.00	0.03 (37%)	0.01

Table 3.1.--Estimates of exploitable biomass (kt), exploitation rate (%), relative biomass (B/B_{MSY}), and relative exploitation rate (H/H_{MSY}) of North Pacific swordfish in subarea 1 under the two-stock scenario during 1951-2006.

	Exploitable Biomass (B)			Exploitation Rate (H)			Relative Biomass (B/BMSY)			Relative Explotation (H/HMSY)		
Year	Mean	Lower 95% CI	Upper 95% CI	Mean	Lower 95% CI	Upper 95% CI	Mean	Lower 95% CI	Upper 95% CI	Mean	Lower 95% CI	Upper 95% CI
1951	96.3	58.9	149.3	0.13	0.08	0.20	1.69	1.22	2.27	0.50	0.32	0.74
1952	80.6	48.2	127.7	0.15	0.09	0.24	1.41	1.03	1.87	0.60	0.37	0.89
1953	74.2	44.1	118.3	0.18	0.10	0.28	1.30	0.94	1.73	0.70	0.42	1.04
1954	76.9	46.1	122.6	0.19	0.11	0.30	1.34	0.96	1.81	0.74	0.44	1.11
1955	74.2	44.5	119.1	0.20	0.12	0.32	1.30	0.93	1.75	0.79	0.47	1.19
1956	70.3	42.2	112.2	0.23	0.14	0.37	1.23	0.89	1.65	0.92	0.55	1.38
1957	71.3	42.9	113.5	0.23	0.13	0.35	1.25	0.90	1.67	0.88	0.53	1.32
1958	77.5	47.4	122.9	0.27	0.16	0.42	1.36	0.99	1.82	1.06	0.64	1.56
1959	72.6	44.0	115.8	0.27	0.16	0.43	1.27	0.93	1.70	1.07	0.65	1.58
1960	72.9	44.4	115.7	0.32	0.19	0.49	1.27	0.94	1.70	1.25	0.76	1.84
1961	69.1	40.9	111.7	0.33	0.19	0.52	1.20	0.87	1.62	1.27	0.76	1.90
1962	64.8	36.6	107.7	0.20	0.11	0.33	1.13	0.79	1.55	0.77	0.45	1.18
1963	69.2	39.7	113.5	0.16	0.09	0.26	1.21	0.84	1.67	0.63	0.36	0.96
1964	70.8	41.1	115.3	0.12	0.07	0.19	1.24	0.86	1.70	0.46	0.27	0.72
1965	75.6	44.9	121.2	0.15	0.09	0.23	1.32	0.92	1.81	0.58	0.34	0.90
1966	74.1	44.0	119.2	0.16	0.09	0.25	1.30	0.91	1.78	0.63	0.36	0.97
1967	68.5	40.4	110.0	0.18	0.11	0.29	1.20	0.84	1.64	0.72	0.42	1.10
1968	64.2	37.7	103.5	0.19	0.11	0.30	1.12	0.79	1.54	0.73	0.42	1.12
1969	64.1	37.4	103.5	0.15	0.08	0.23	1.12	0.78	1.54	0.57	0.33	0.88
1970	67.0	39.3	107.3	0.14	0.08	0.22	1.17	0.82	1.61	0.55	0.31	0.84
1971	68.4	40.3	109.8	0.12	0.07	0.19	1.20	0.83	1.65	0.48	0.27	0.74
1972	70.3	41.6	113.2	0.11	0.06	0.17	1.23	0.86	1.69	0.43	0.25	0.67
1973	76.2	45.4	121.7	0.10	0.06	0.16	1.33	0.93	1.82	0.41	0.24	0.63
1974	81.3	48.7	129.0	0.11	0.06	0.17	1.42	1.00	1.94	0.43	0.25	0.65
1975	81.1	48.6	129.1	0.14	0.08	0.22	1.42	1.00	1.92	0.55	0.33	0.85
1976	81.0	48.3	129.6	0.16	0.09	0.24	1.42	1.00	1.93	0.61	0.36	0.93
1977	75.7	44.6	121.5	0.16	0.09	0.25	1.32	0.94	1.79	0.61	0.36	0.93
1978	73.1	43.2	117.1	0.18	0.11	0.28	1.28	0.91	1.73	0.70	0.42	1.07
1979	75.0	44.0	120.6	0.15	0.09	0.24	1.31	0.93	1.77	0.58	0.35	0.89
1980	81.1	47.8	130.3	0.12	0.07	0.19	1.42	1.00	1.93	0.46	0.27	0.71
1981	83.1	49.4	133.4	0.13	0.07	0.20	1.45	1.03	1.97	0.49	0.30	0.75
1982	85.6	50.9	137.6	0.12	0.07	0.18	1.50	1.07	2.01	0.46	0.28	0.69
1983	96.4	57.4	154.4	0.13	0.07	0.20	1.68	1.21	2.25	0.49	0.30	0.74
1984	99.4	58.7	159.8	0.14	0.08	0.22	1.73	1.27	2.32	0.53	0.33	0.79
1985	109.4	64.1	177.2	0.15	0.08	0.23	1.91	1.39	2.57	0.57	0.35	0.85
1986	109.7	63.3	178.9	0.13	0.07	0.20	1.91	1.38	2.57	0.49	0.30	0.72
1987	113.4	66.1	185.2	0.12	0.07	0.20	1.97	1.43	2.68	0.48	0.29	0.71
1988	109.1	63.6	178.2	0.11	0.06	0.18	1.90	1.37	2.58	0.44	0.27	0.66
1989	101.0	59.1	163.9	0.12	0.07	0.18	1.76	1.28	2.36	0.45	0.28	0.67
1990	101.9	60.2	164.5	0.12	0.07	0.18	1.78	1.29	2.39	0.46	0.28	0.68
1991	97.4	57.8	156.6	0.13	0.07	0.20	1.70	1.23	2.27	0.50	0.30	0.74
1992	96.9	57.9	155.4	0.18	0.10	0.28	1.69	1.22	2.28	0.69	0.42	1.04
1993	88.4	52.2	142.8	0.21	0.12	0.33	1.54	1.10	2.10	0.82	0.49	1.25
1994	73.3	42.5	119.3	0.20	0.12	0.32	1.28	0.91	1.74	0.78	0.47	1.19
1995	61.9	36.3	100.5	0.22	0.12	0.34	1.08	0.78	1.46	0.84	0.50	1.26
1996	58.3	34.5	93.9	0.22	0.13	0.34	1.02	0.73	1.37	0.84	0.50	1.27
1997	53.5	32.0	86.0	0.25	0.15	0.39	0.93	0.67	1.26	0.98	0.58	1.47
1998	53.3	31.7	85.4	0.25	0.14	0.39	0.93	0.67	1.25	0.96	0.57	1.45
1999	59.4	35.5	94.9	0.24	0.14	0.37	1.04	0.75	1.39	0.92	0.55	1.39
2000	67.1	40.3	106.8	0.23	0.13	0.36	1.17	0.84	1.58	0.90	0.53	1.36
2001	72.1	42.5	116.3	0.15	0.09	0.25	1.26	0.89	1.73	0.61	0.35	0.93
2002	72.6	43.2	116.4	0.15	0.09	0.24	1.27	0.89	1.74	0.59	0.34	0.91
2003	68.1	40.5	108.6	0.17	0.10	0.26	1.19	0.84	1.62	0.66	0.38	1.01
2004	68.0	40.7	108.5	0.16	0.10	0.26	1.19	0.85	1.61	0.64	0.37	0.98
2005	70.0	42.0	111.3	0.17	0.10	0.26	1.22	0.87	1.65	0.65	0.38	1.00
2006	74.9	44.8	119.5	0.14	0.08	0.22	1.31	0.92	1.78	0.55	0.32	0.86
Average 1951-2006	77.9	46.1	125.1	0.17	0.10	0.27	1.36	0.97	1.84	0.67	0.40	1.01
Average 1997-2006	65.9	39.3	105.4	0.19	0.11	0.30	1.15	0.82	1.56	0.74	0.44	1.13

Table 3.2.--Estimates of exploitable biomass (kt), exploitation rate (%), relative biomass (B/B_{MSY}), and relative exploitation rate (H/H_{MSY}) of North Pacific swordfish in subarea 2 under the two-stock scenario during 1951–2006.

	Exploitable Biomass (B)			Exploitation Rate (H)			Relative Biomass (B/BMSY)			Relative Explotation (H/HMSY)		
Year	Mean	Lower 95% CI	Upper 95% CI	Mean	Lower 95% CI	Upper 95% CI	Mean	Lower 95% CI	Upper 95% CI	Mean	Lower 95% CI	Upper 95% CI
1951	43.0	20.9	78.1	0.00	0.00	0.00	1.75	1.08	2.63	0.00	0.00	0.00
1952	38.1	16.8	74.0	0.00	0.00	0.00	1.55	0.83	2.64	0.00	0.00	0.00
1953	32.3	12.7	65.6	0.00	0.00	0.00	1.32	0.61	2.38	0.00	0.00	0.00
1954	26.7	9.7	53.4	0.00	0.00	0.00	1.09	0.45	1.92	0.01	0.00	0.02
1955	21.6	8.9	41.8	0.00	0.00	0.00	0.88	0.42	1.50	0.00	0.00	0.01
1956	20.8	8.8	40.1	0.00	0.00	0.00	0.85	0.43	1.46	0.00	0.00	0.01
1957	29.2	13.5	54.1	0.00	0.00	0.01	1.20	0.64	2.00	0.04	0.01	0.10
1958	27.1	12.4	50.7	0.00	0.00	0.01	1.11	0.60	1.86	0.03	0.01	0.07
1959	24.0	10.6	46.0	0.00	0.00	0.01	0.98	0.52	1.68	0.03	0.01	0.07
1960	27.3	12.2	51.8	0.00	0.00	0.01	1.12	0.60	1.90	0.04	0.01	0.09
1961	35.7	16.5	66.0	0.01	0.01	0.03	1.46	0.80	2.45	0.13	0.05	0.32
1962	43.0	20.1	79.2	0.02	0.01	0.04	1.76	0.98	2.95	0.19	0.07	0.46
1963	48.4	22.8	89.2	0.03	0.01	0.06	1.98	1.11	3.33	0.28	0.10	0.69
1964	49.4	23.0	91.2	0.03	0.02	0.06	2.02	1.13	3.40	0.30	0.10	0.73
1965	47.7	21.8	89.1	0.02	0.01	0.04	1.95	1.08	3.30	0.18	0.06	0.43
1966	49.5	22.8	91.9	0.03	0.01	0.05	2.03	1.12	3.42	0.24	0.08	0.58
1967	49.8	22.7	92.9	0.02	0.01	0.04	2.04	1.12	3.44	0.20	0.07	0.48
1968	53.0	24.6	98.4	0.03	0.01	0.05	2.17	1.20	3.69	0.25	0.09	0.59
1969	59.3	27.8	109.1	0.07	0.03	0.13	2.43	1.36	4.12	0.61	0.22	1.47
1970	61.2	28.3	113.9	0.04	0.02	0.08	2.51	1.40	4.28	0.40	0.14	0.98
1971	55.1	25.1	102.9	0.03	0.01	0.05	2.26	1.23	3.88	0.24	0.09	0.57
1972	53.7	24.3	100.3	0.03	0.01	0.06	2.20	1.21	3.75	0.29	0.10	0.69
1973	56.9	26.3	105.5	0.05	0.02	0.09	2.33	1.28	3.92	0.44	0.16	1.08
1974	57.1	26.2	106.2	0.03	0.01	0.05	2.34	1.29	3.97	0.25	0.09	0.60
1975	56.6	26.1	105.3	0.03	0.01	0.06	2.32	1.29	3.92	0.28	0.10	0.66
1976	55.2	25.6	102.4	0.04	0.02	0.07	2.26	1.26	3.81	0.36	0.13	0.87
1977	54.9	25.5	101.4	0.04	0.02	0.09	2.25	1.25	3.81	0.42	0.15	1.01
1978	49.3	22.7	92.2	0.04	0.02	0.08	2.02	1.11	3.43	0.39	0.14	0.93
1979	45.5	20.8	84.9	0.04	0.02	0.07	1.86	1.03	3.14	0.34	0.12	0.82
1980	43.5	20.0	81.0	0.05	0.02	0.10	1.78	0.98	3.01	0.48	0.17	1.17
1981	39.3	18.0	73.4	0.09	0.04	0.17	1.61	0.88	2.72	0.80	0.28	1.93
1982	35.4	16.0	66.7	0.08	0.04	0.16	1.44	0.78	2.46	0.74	0.26	1.79
1983	33.3	14.8	62.8	0.05	0.02	0.10	1.36	0.73	2.32	0.45	0.16	1.10
1984	28.2	12.3	54.3	0.04	0.02	0.07	1.15	0.61	1.98	0.34	0.12	0.82
1985	30.6	13.7	58.2	0.04	0.02	0.07	1.25	0.67	2.12	0.34	0.12	0.83
1986	36.3	16.8	67.4	0.06	0.03	0.11	1.49	0.82	2.50	0.56	0.20	1.34
1987	40.0	18.7	74.1	0.07	0.03	0.13	1.64	0.91	2.77	0.64	0.22	1.54
1988	37.4	17.3	69.8	0.08	0.04	0.14	1.53	0.85	2.60	0.70	0.25	1.67
1989	37.1	17.2	68.9	0.07	0.03	0.14	1.52	0.84	2.58	0.68	0.24	1.62
1990	38.3	18.1	70.6	0.14	0.07	0.26	1.57	0.87	2.63	1.26	0.45	3.00
1991	34.8	15.8	65.5	0.09	0.04	0.17	1.42	0.78	2.43	0.82	0.29	1.97
1992	35.0	16.2	65.5	0.12	0.06	0.23	1.43	0.78	2.44	1.11	0.39	2.66
1993	34.8	15.9	65.3	0.10	0.04	0.18	1.42	0.78	2.41	0.88	0.31	2.12
1994	34.2	15.6	64.3	0.09	0.04	0.16	1.40	0.77	2.38	0.78	0.28	1.88
1995	36.3	16.7	67.4	0.07	0.03	0.13	1.49	0.82	2.51	0.61	0.22	1.44
1996	44.3	20.8	81.5	0.06	0.03	0.11	1.82	1.03	3.05	0.51	0.19	1.22
1997	52.8	25.6	95.5	0.10	0.05	0.18	2.17	1.24	3.60	0.89	0.33	2.13
1998	52.5	24.9	96.5	0.13	0.06	0.24	2.15	1.21	3.62	1.15	0.43	2.72
1999	50.0	22.6	93.8	0.06	0.03	0.11	2.05	1.12	3.51	0.52	0.19	1.23
2000	62.3	29.3	114.0	0.08	0.04	0.14	2.56	1.44	4.33	0.70	0.26	1.64
2001	71.9	33.8	131.8	0.08	0.04	0.14	2.95	1.65	4.98	0.70	0.26	1.66
2002	68.8	31.5	127.3	0.07	0.03	0.14	2.82	1.56	4.80	0.67	0.25	1.58
2003	65.2	30.0	120.5	0.07	0.03	0.12	2.67	1.48	4.51	0.60	0.22	1.41
2004	60.8	28.1	113.3	0.05	0.02	0.09	2.49	1.39	4.22	0.45	0.16	1.06
2005	56.1	25.7	105.2	0.04	0.02	0.08	2.29	1.29	3.92	0.36	0.13	0.86
2006	59.7	27.7	111.1	0.03	0.02	0.06	2.44	1.38	4.15	0.30	0.11	0.73
Average 1951-2006	44.5	20.4	82.9	0.05	0.02	0.09	1.82	1.00	3.08	0.43	0.15	1.03
Average 1997-2006	60.0	27.9	110.9	0.07	0.03	0.13	2.46	1.38	4.16	0.63	0.23	1.50

Table 3.3.--Estimates of exploitable biomass (kt), exploitation rate (%), relative biomass (B/B_{MSY}), and relative exploitation rate (H/H_{MSY}) of North Pacific swordfish under the single-stock scenario during 1951–2006.

	Exploitable Biomass (B)			Exploitation Rate (H)			Relative Biomass (B/BMSY)			Relative Explotation (H/HMSY)		
Year	Mean	Lower 95% CI	Upper 95% CI	Mean	Lower 95% CI	Upper 95% CI	Mean	Lower 95% CI	Upper 95% CI	Mean	Lower 95% CI	Upper 95% CI
1951	97.9	57.4	156.0	0.13	0.07	0.20	1.68	1.21	2.29	0.38	0.23	0.58
1952	84.5	48.7	136.6	0.15	0.09	0.24	1.45	1.06	1.91	0.45	0.26	0.69
1953	79.0	45.7	128.3	0.17	0.10	0.27	1.35	0.98	1.80	0.51	0.29	0.79
1954	82.8	48.1	134.5	0.18	0.10	0.28	1.42	1.03	1.91	0.53	0.30	0.84
1955	78.6	45.3	128.5	0.19	0.11	0.31	1.35	0.97	1.81	0.58	0.33	0.91
1956	74.1	42.9	120.6	0.22	0.13	0.36	1.27	0.92	1.69	0.67	0.38	1.06
1957	75.9	44.0	123.5	0.22	0.12	0.35	1.30	0.95	1.73	0.65	0.37	1.02
1958	79.6	46.6	128.8	0.27	0.15	0.42	1.37	1.00	1.82	0.80	0.45	1.24
1959	73.2	42.1	119.6	0.28	0.16	0.45	1.25	0.92	1.66	0.83	0.47	1.27
1960	74.7	43.3	121.9	0.32	0.18	0.51	1.28	0.95	1.69	0.95	0.54	1.46
1961	72.8	41.2	120.8	0.32	0.18	0.52	1.25	0.92	1.67	0.96	0.54	1.48
1962	71.0	38.6	119.2	0.19	0.11	0.33	1.21	0.86	1.64	0.58	0.32	0.92
1963	77.0	43.2	127.8	0.16	0.09	0.27	1.32	0.93	1.80	0.49	0.27	0.79
1964	78.8	44.8	129.2	0.13	0.07	0.21	1.35	0.95	1.83	0.38	0.21	0.61
1965	81.5	47.1	132.8	0.15	0.09	0.24	1.40	0.99	1.89	0.45	0.25	0.73
1966	81.0	46.8	131.4	0.16	0.09	0.26	1.39	0.99	1.87	0.49	0.27	0.79
1967	76.6	44.0	124.6	0.18	0.10	0.29	1.31	0.94	1.77	0.54	0.30	0.86
1968	74.7	42.5	121.4	0.18	0.10	0.29	1.28	0.91	1.72	0.54	0.30	0.86
1969	77.5	44.6	126.7	0.17	0.10	0.27	1.33	0.95	1.79	0.51	0.28	0.81
1970	81.8	47.1	133.2	0.15	0.08	0.24	1.40	1.00	1.89	0.44	0.25	0.70
1971	82.8	47.5	134.7	0.12	0.07	0.19	1.42	1.01	1.90	0.35	0.20	0.57
1972	85.2	49.4	138.5	0.11	0.06	0.18	1.46	1.05	1.94	0.33	0.19	0.53
1973	90.4	52.9	145.7	0.12	0.07	0.19	1.55	1.12	2.06	0.35	0.20	0.56
1974	90.0	52.4	145.0	0.11	0.07	0.18	1.54	1.11	2.05	0.35	0.20	0.55
1975	85.5	49.5	138.0	0.15	0.09	0.25	1.47	1.06	1.94	0.46	0.27	0.73
1976	85.2	49.4	138.0	0.17	0.10	0.28	1.46	1.06	1.94	0.52	0.30	0.82
1977	81.5	46.7	132.7	0.17	0.10	0.28	1.40	1.01	1.87	0.52	0.29	0.83
1978	76.9	44.0	125.8	0.20	0.11	0.32	1.32	0.95	1.76	0.59	0.33	0.94
1979	75.1	42.6	123.2	0.17	0.10	0.28	1.29	0.92	1.73	0.52	0.29	0.82
1980	78.9	44.9	129.1	0.15	0.08	0.24	1.35	0.96	1.83	0.45	0.25	0.72
1981	78.1	44.9	126.9	0.18	0.10	0.29	1.34	0.96	1.80	0.53	0.30	0.85
1982	78.1	44.7	127.7	0.16	0.09	0.27	1.34	0.96	1.78	0.49	0.28	0.78
1983	86.5	49.8	140.3	0.16	0.09	0.26	1.48	1.07	1.97	0.48	0.27	0.75
1984	87.7	50.4	143.3	0.17	0.09	0.27	1.50	1.11	1.97	0.50	0.29	0.77
1985	97.9	56.0	160.0	0.18	0.10	0.29	1.68	1.25	2.20	0.53	0.31	0.80
1986	101.8	57.2	168.1	0.16	0.09	0.26	1.74	1.30	2.30	0.47	0.28	0.71
1987	107.3	60.0	177.3	0.16	0.09	0.26	1.83	1.35	2.44	0.47	0.28	0.70
1988	100.0	56.0	165.9	0.15	0.08	0.25	1.71	1.26	2.27	0.45	0.27	0.69
1989	96.0	54.3	158.1	0.15	0.08	0.25	1.64	1.22	2.16	0.45	0.26	0.68
1990	97.1	55.3	159.1	0.17	0.10	0.28	1.66	1.23	2.19	0.52	0.31	0.80
1991	89.3	50.8	146.5	0.17	0.10	0.28	1.53	1.13	2.00	0.52	0.30	0.79
1992	89.5	51.8	146.0	0.24	0.14	0.38	1.53	1.14	2.02	0.71	0.42	1.10
1993	82.1	46.4	134.9	0.27	0.15	0.44	1.40	1.03	1.87	0.80	0.46	1.24
1994	72.1	40.2	119.7	0.24	0.14	0.41	1.23	0.90	1.65	0.73	0.41	1.14
1995	66.4	37.7	108.8	0.24	0.13	0.39	1.14	0.84	1.50	0.71	0.40	1.10
1996	69.0	39.4	113.0	0.22	0.12	0.35	1.18	0.86	1.57	0.65	0.37	1.02
1997	68.3	39.5	110.8	0.27	0.15	0.43	1.17	0.86	1.54	0.81	0.46	1.24
1998	68.4	39.5	111.0	0.28	0.16	0.46	1.17	0.87	1.53	0.85	0.49	1.30
1999	76.7	43.9	125.8	0.22	0.12	0.36	1.31	0.98	1.71	0.66	0.38	1.01
2000	96.8	55.3	158.2	0.21	0.12	0.34	1.66	1.24	2.17	0.62	0.36	0.94
2001	109.9	60.9	182.4	0.15	0.08	0.25	1.88	1.38	2.51	0.45	0.26	0.69
2002	102.8	58.0	169.2	0.15	0.09	0.25	1.76	1.30	2.32	0.46	0.27	0.70
2003	92.6	52.9	151.6	0.17	0.10	0.27	1.58	1.19	2.07	0.50	0.30	0.76
2004	89.9	51.7	146.6	0.16	0.09	0.25	1.54	1.15	2.00	0.47	0.27	0.71
2005	88.5	51.1	143.8	0.16	0.09	0.25	1.51	1.14	1.97	0.47	0.28	0.71
2006	98.0	56.7	159.1	0.13	0.07	0.21	1.68	1.25	2.20	0.38	0.22	0.59
Average 1951-2006	83.8	48.0	137.0	0.18	0.10	0.30	1.44	1.05	1.91	0.55	0.31	0.86
Average 1997-2006	89.2	50.9	145.9	0.19	0.11	0.31	1.52	1.14	2.00	0.57	0.33	0.87

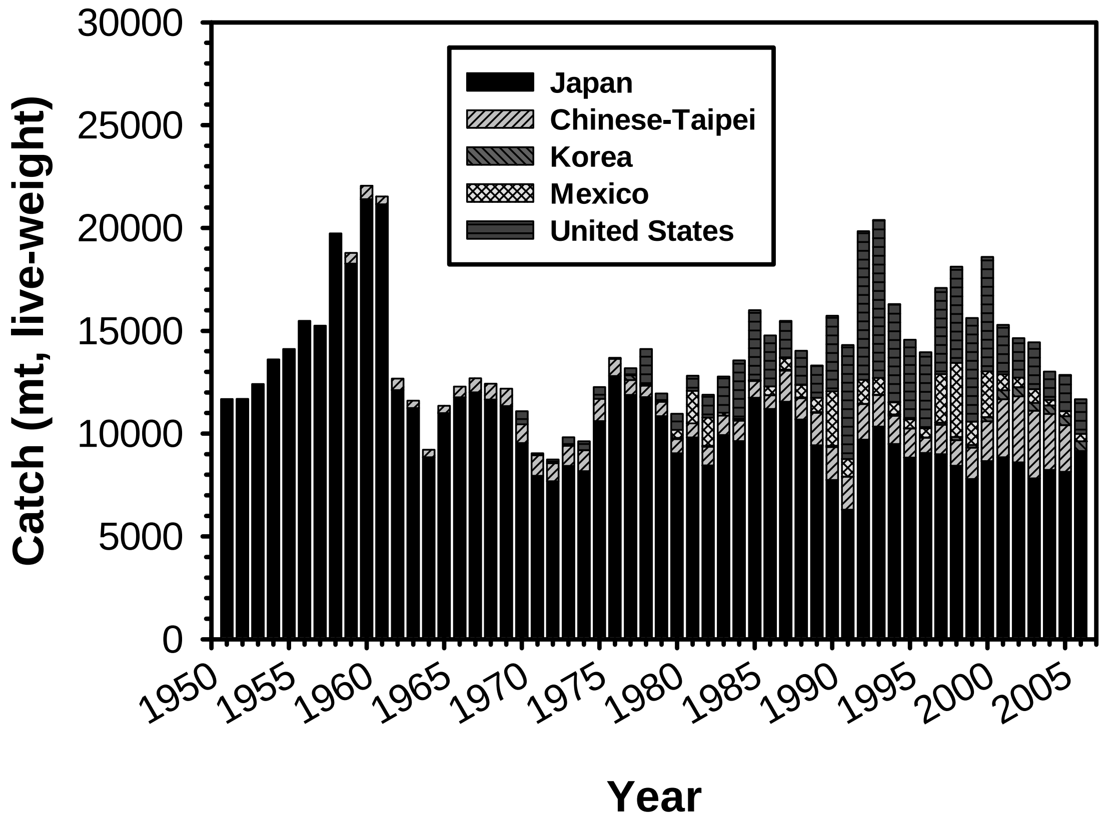
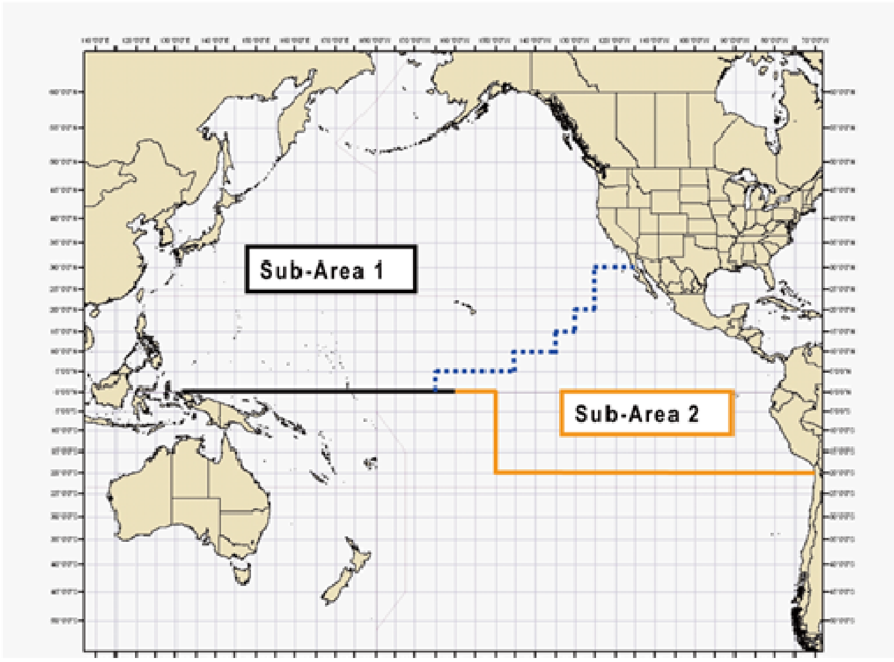


Figure 1.-- Swordfish landings in the North Pacific by Japan, Chinese-Taipei, Korea, Mexico, and the United States.

(a)



(b)

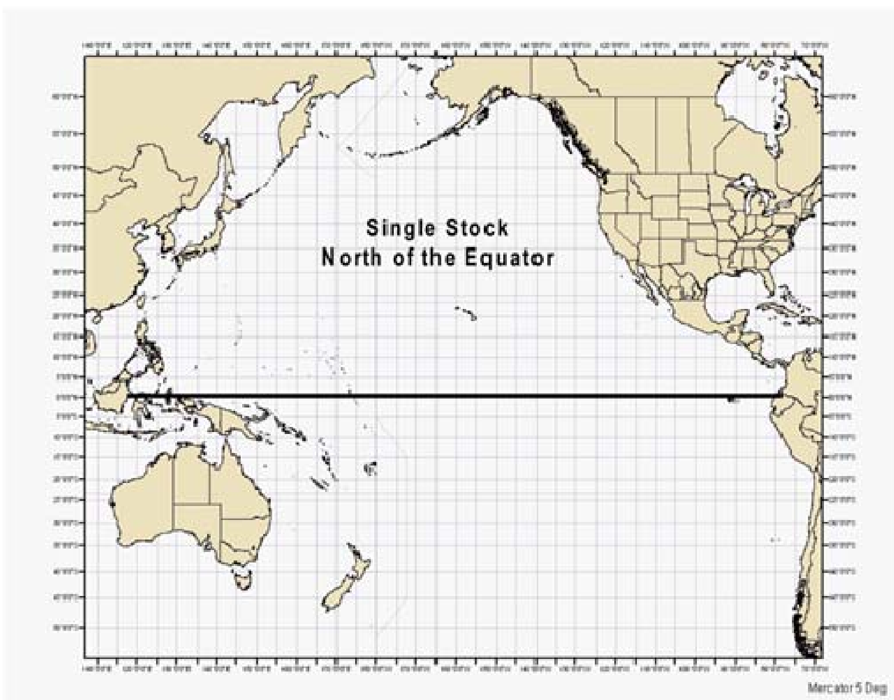
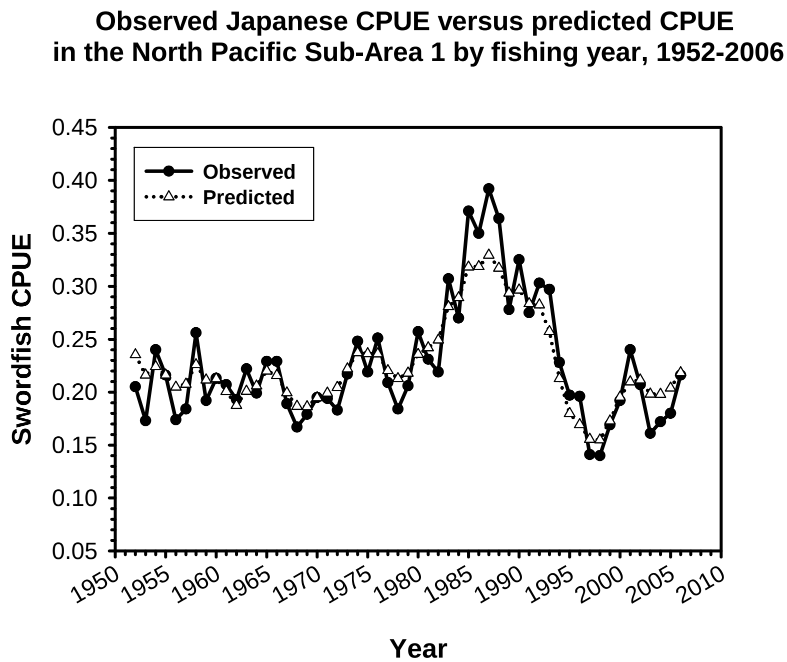


Figure 2.--Stock structure scenarios for the North Pacific swordfish population were (a) the two-stock scenario with stocks in the western and central Pacific (subarea 1) and in the eastern Pacific (subarea 2) and (b) a single- stock scenario covering the North Pacific.



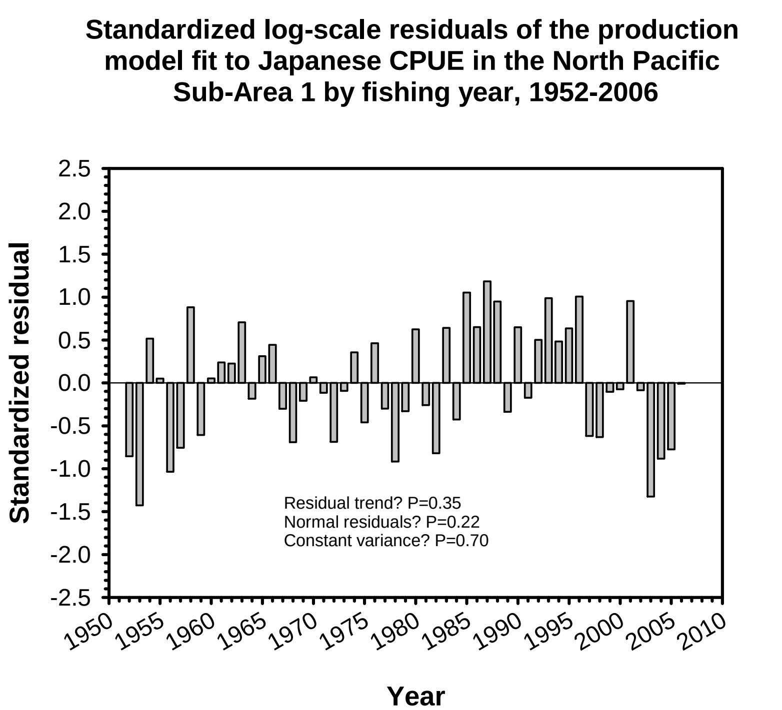
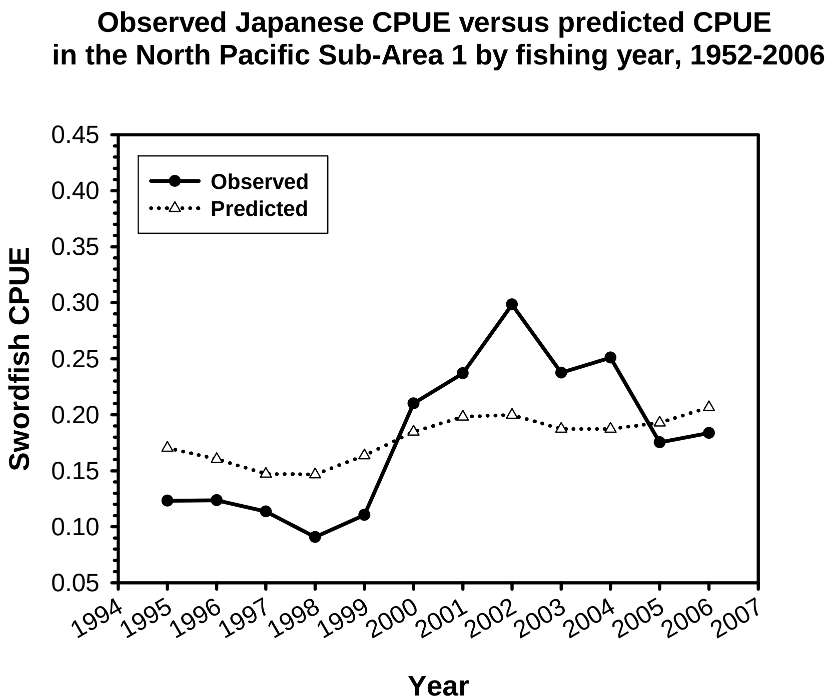


Figure 3.1.--Time series of observed and predicted Japanese longline CPUE of swordfish in subarea 1 along with standardized log-scale residuals of the model fit under the two-stock scenario during 1952–2006.



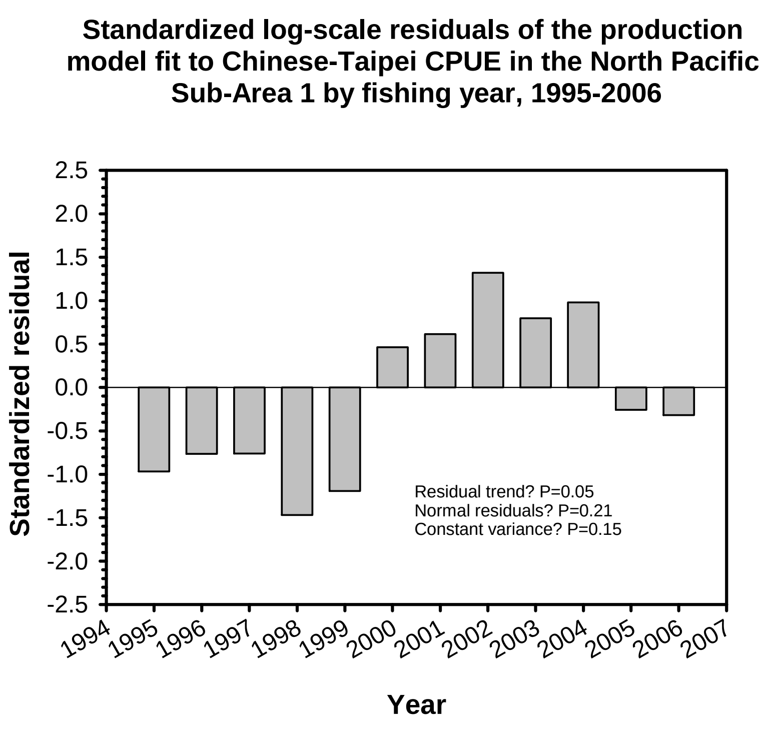
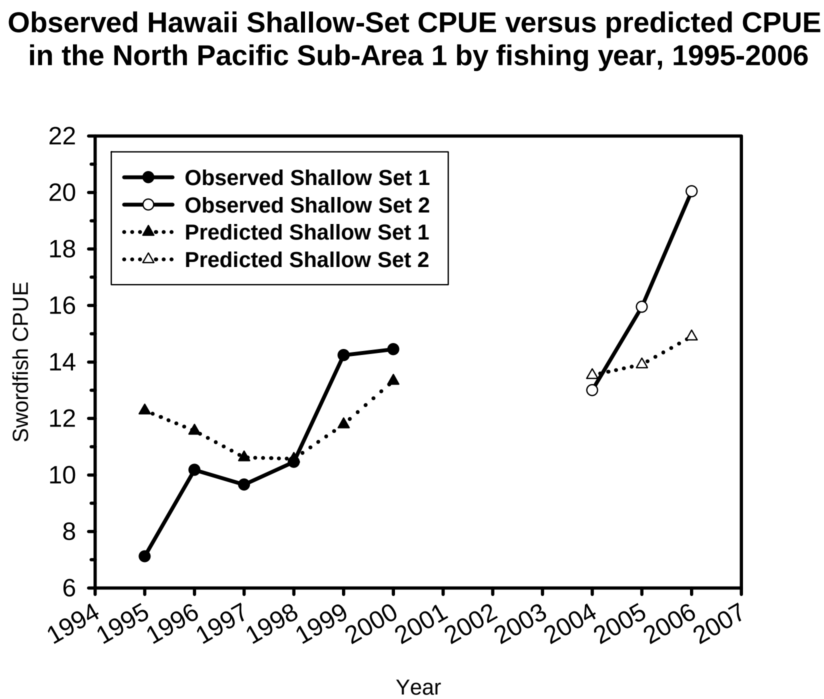


Figure 3.2.--Time series of observed and predicted Taiwanese longline CPUE of swordfish in subarea 1 along with standardized log-scale residuals of the model fit under the two-stock scenario during 1995–2006.



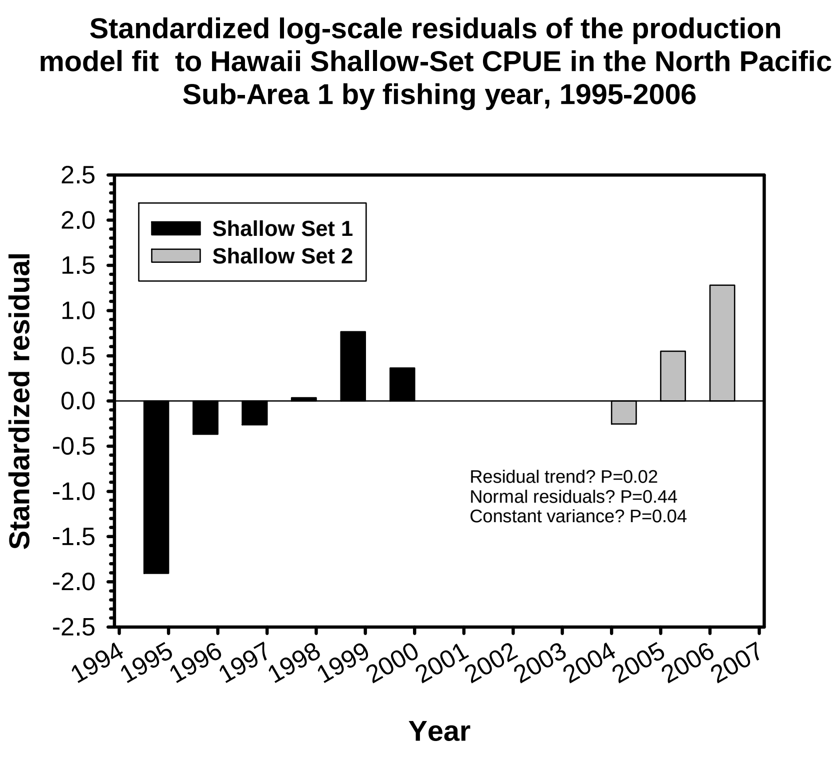
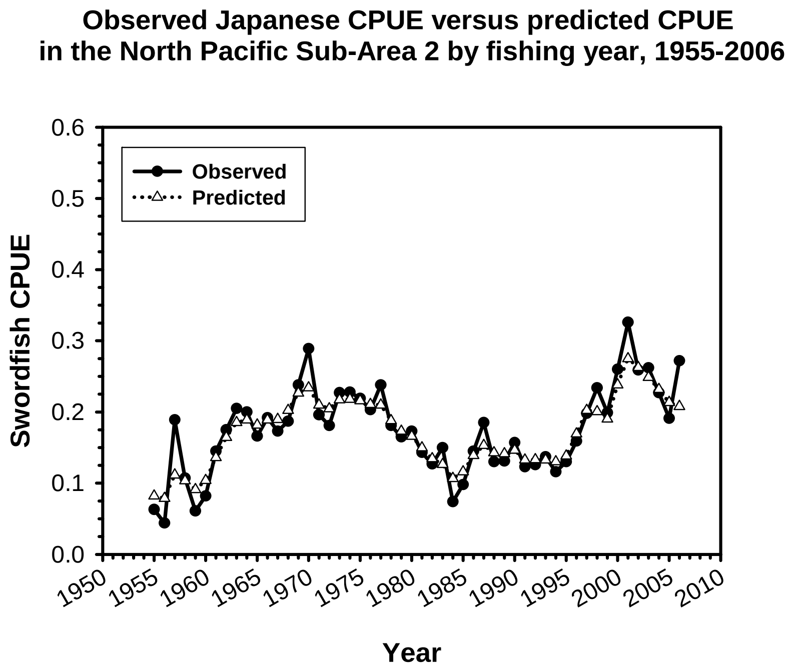


Figure 3.3.--Time series of observed and predicted Hawaii shallow-set longline CPUE of swordfish in subarea 1 along with standardized log-scale residuals of the model fit under the two-stock scenario during 1995–2000 and 2004–2006.



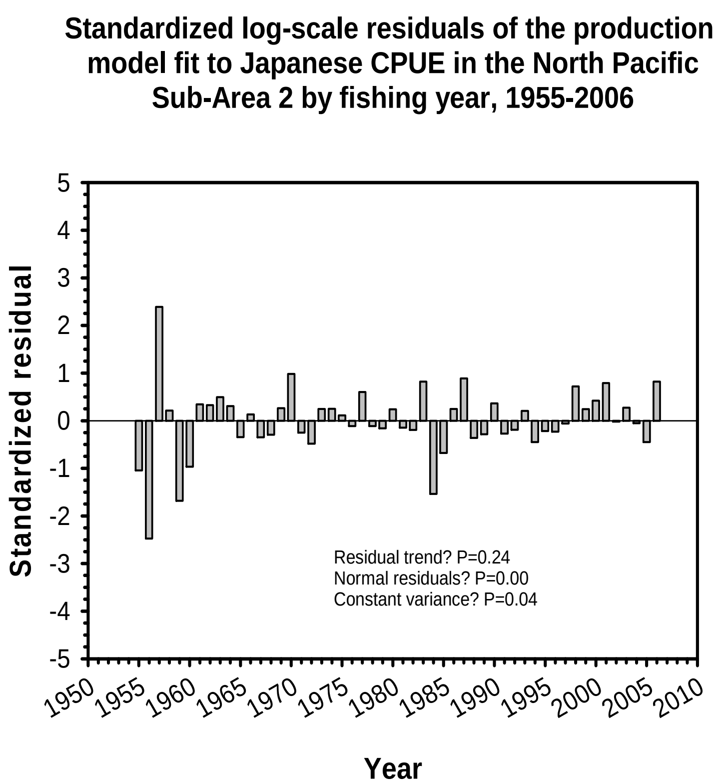
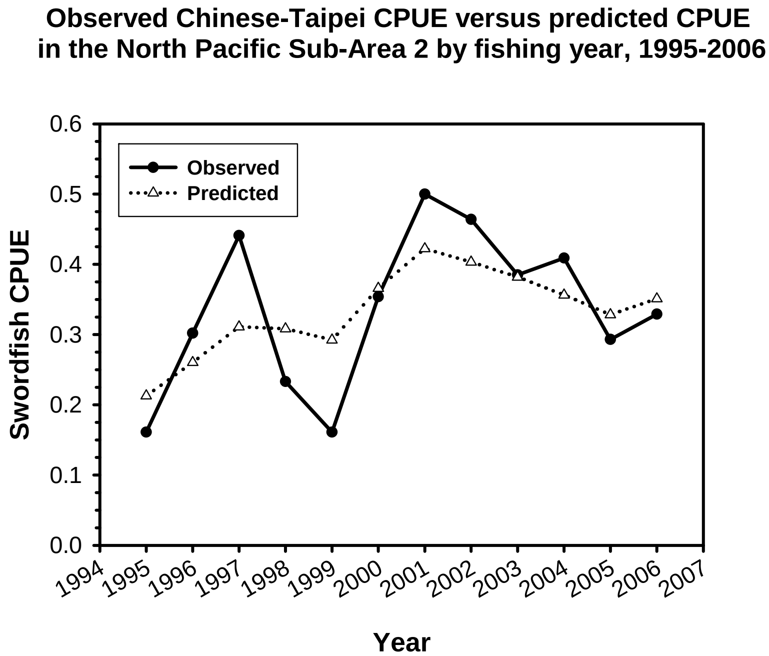


Figure 4.1.--Time series of observed and predicted Japanese longline CPUE of swordfish in subarea 2 along with standardized log-scale residuals of the model fit under the two-stock scenario during 1955-2006.



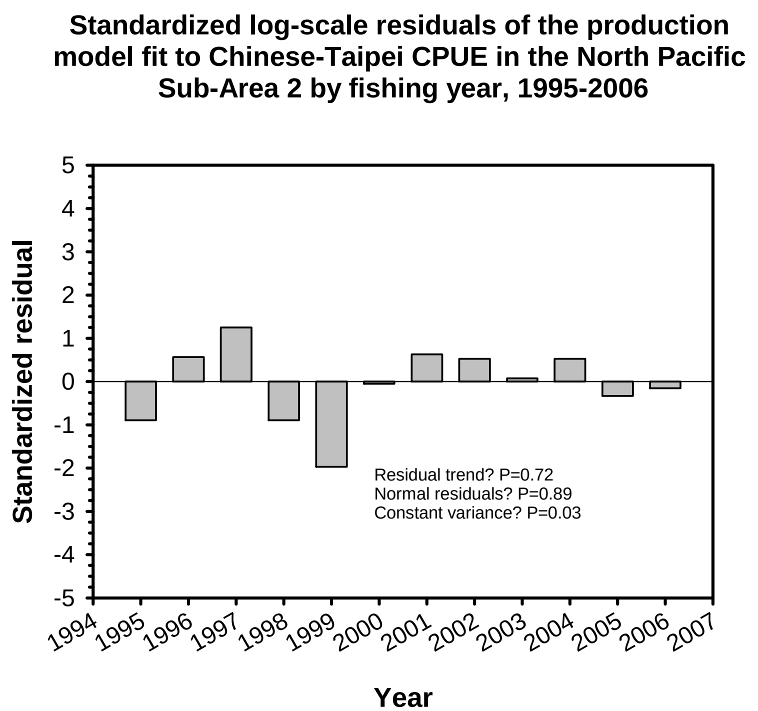
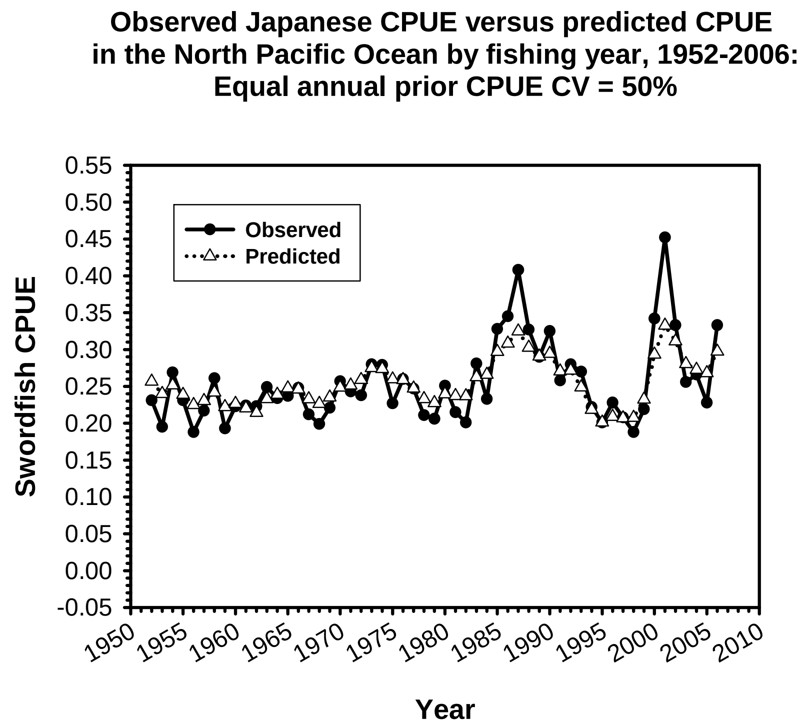


Figure 4.2.--Time series of observed and predicted Taiwanese longline CPUE of swordfish in subarea 2 along with standardized log-scale residuals of the model fit under the two-stock scenario during 1995–2006.



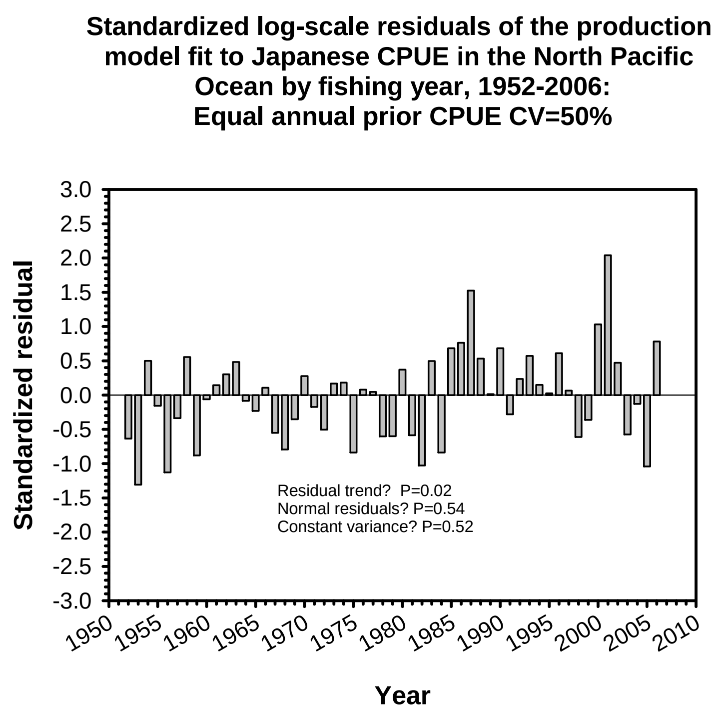
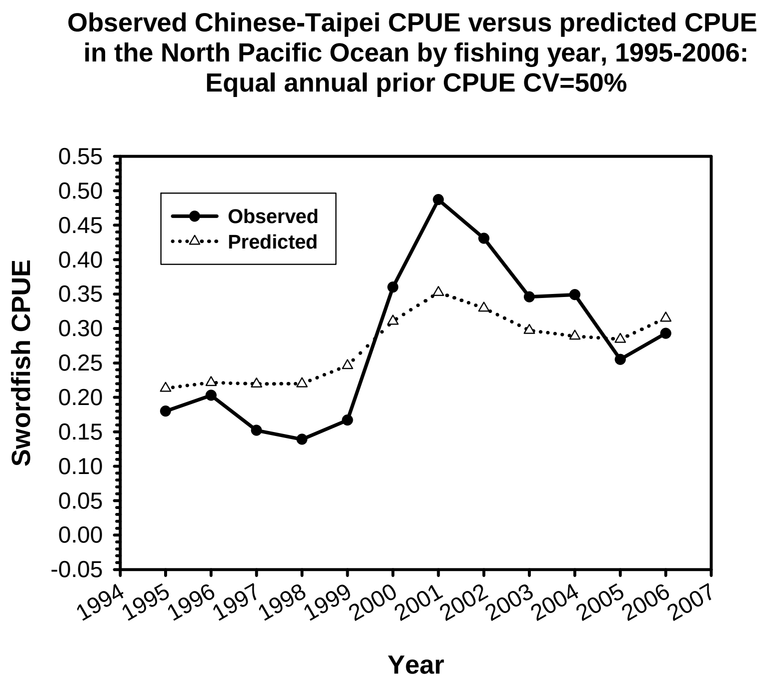


Figure 5.1.--Time series of observed and predicted Japanese longline CPUE of swordfish along with standardized log-scale residuals of the model fit under the single-stock scenario during 1952–2006.



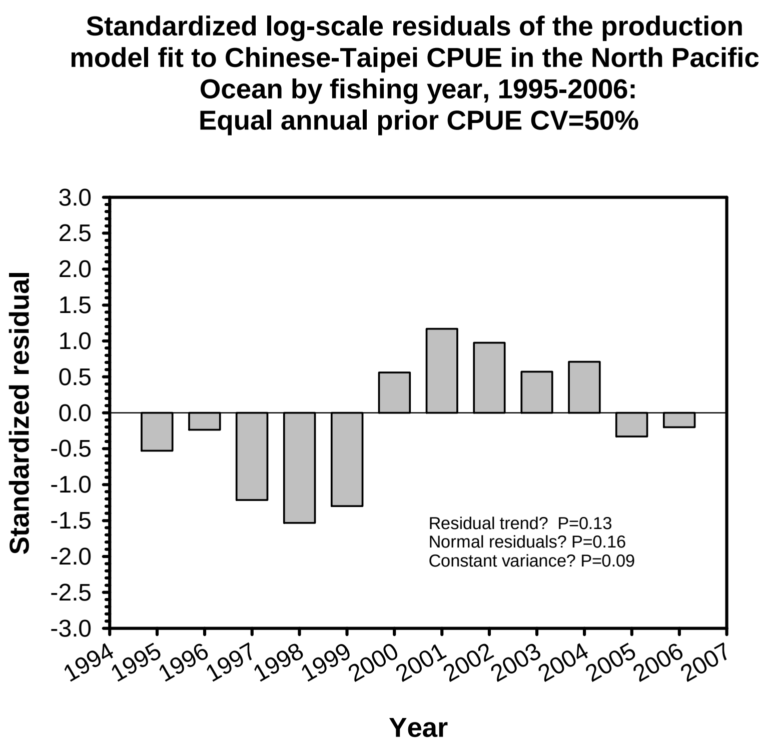
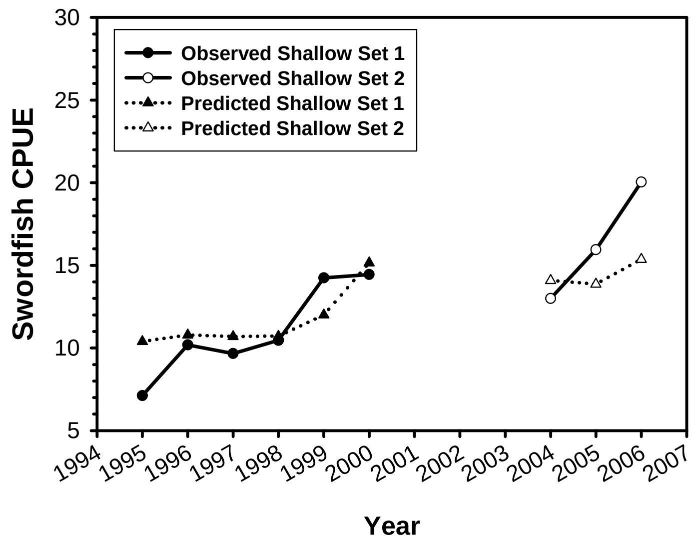


Figure 5.2.--Time series of observed and predicted Taiwanese longline CPUE of swordfish along with standardized log-scale residuals of the model fit under the single-stock scenario during 1995–2006.

Observed Hawaii Shallow-Set CPUE versus predicted CPUE in the North Pacific Ocean by fishing year, 1995-2006: Equal annual CPUE CVs



Standardized log-scale residuals of the production model fit to Hawaii Shallow-Set CPUE in the North Pacific Ocean by fishing year, 1995-2006: Equal annual CPUE CVs

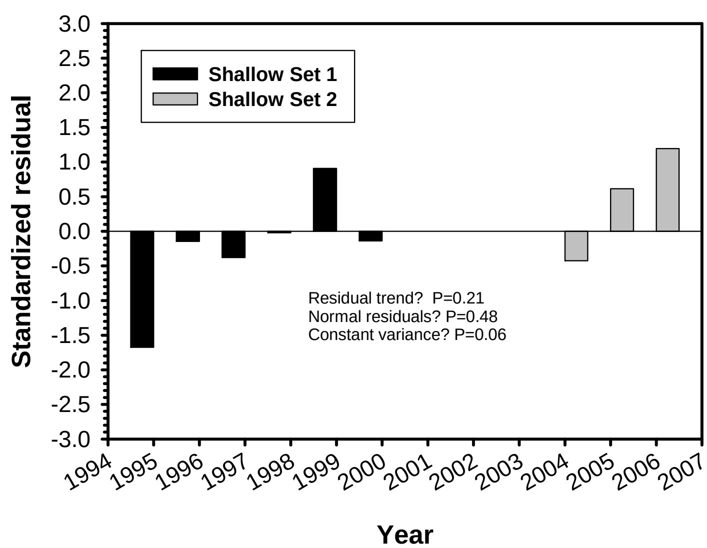
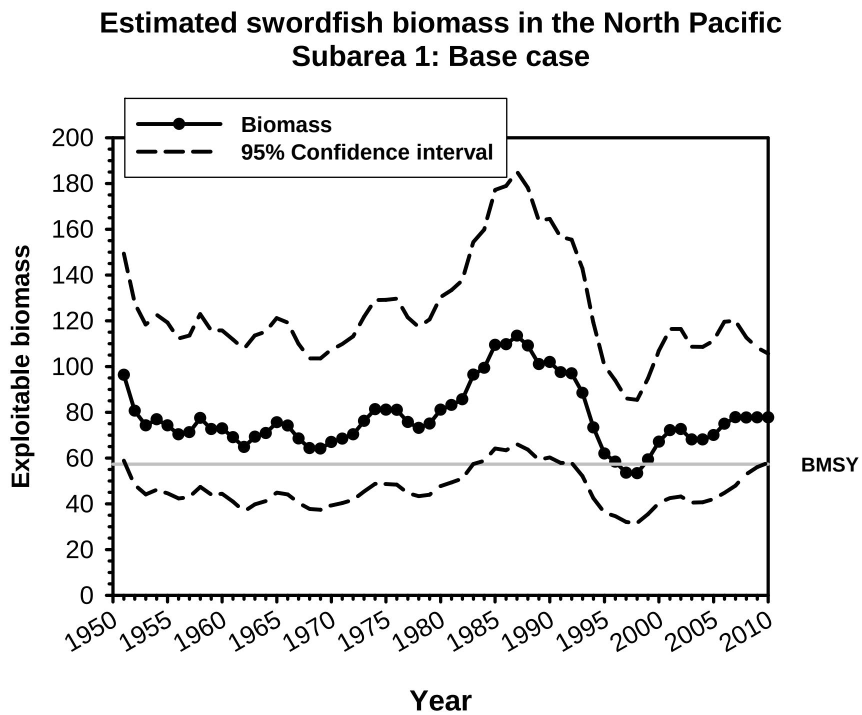


Figure 5.3.--Time series of observed and predicted Hawaii shallow-set longline CPUE of swordfish along with standardized log-scale residuals of the model fit under the single-stock scenario during 1995–2000 and 2004–2006.



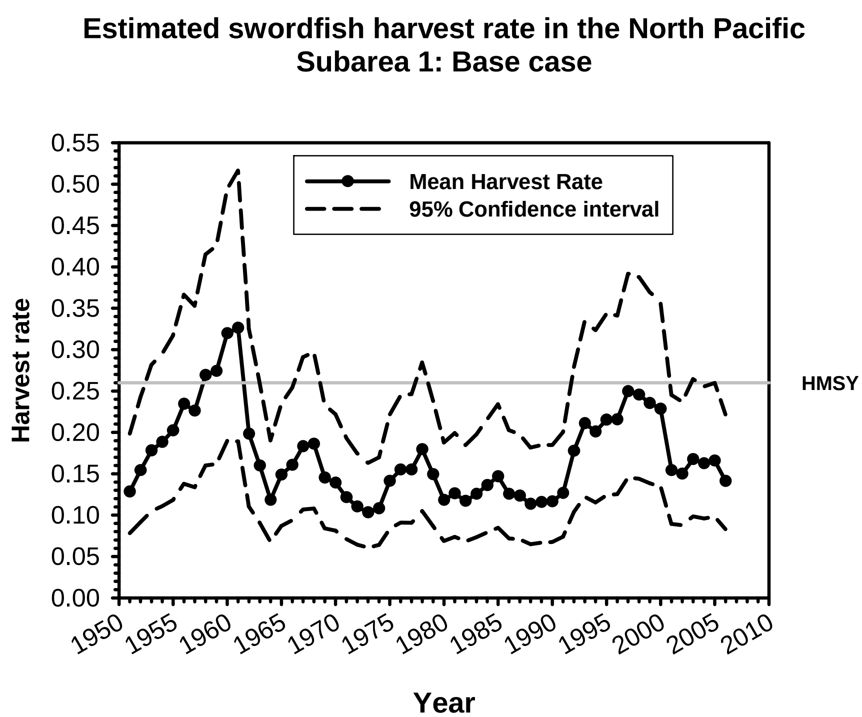
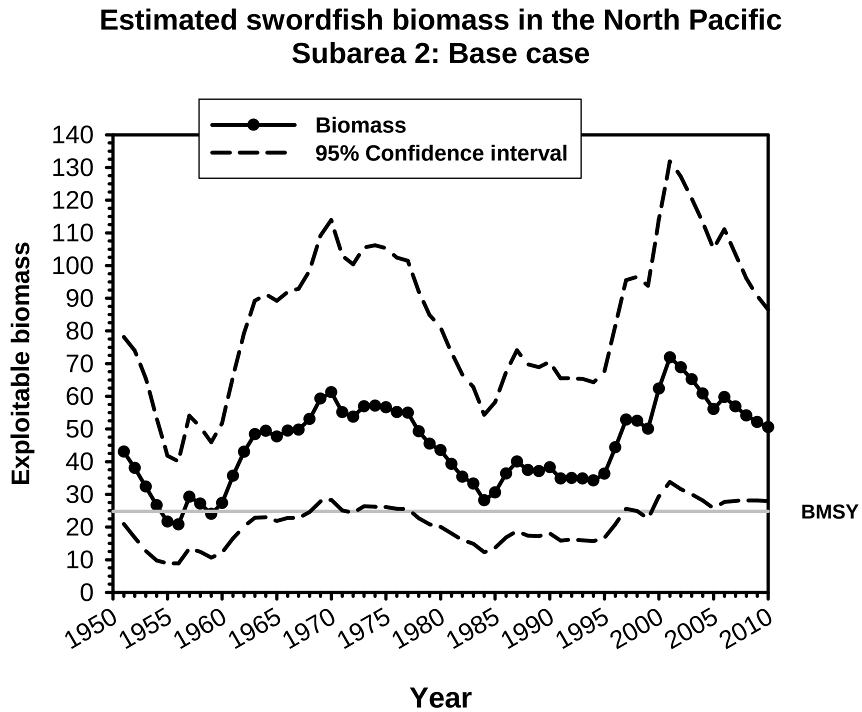


Figure 6.1.--Trends in exploitable biomass and exploitation rate of North Pacific swordfish in subarea 1 under the two-stock scenario, 1951–2006.



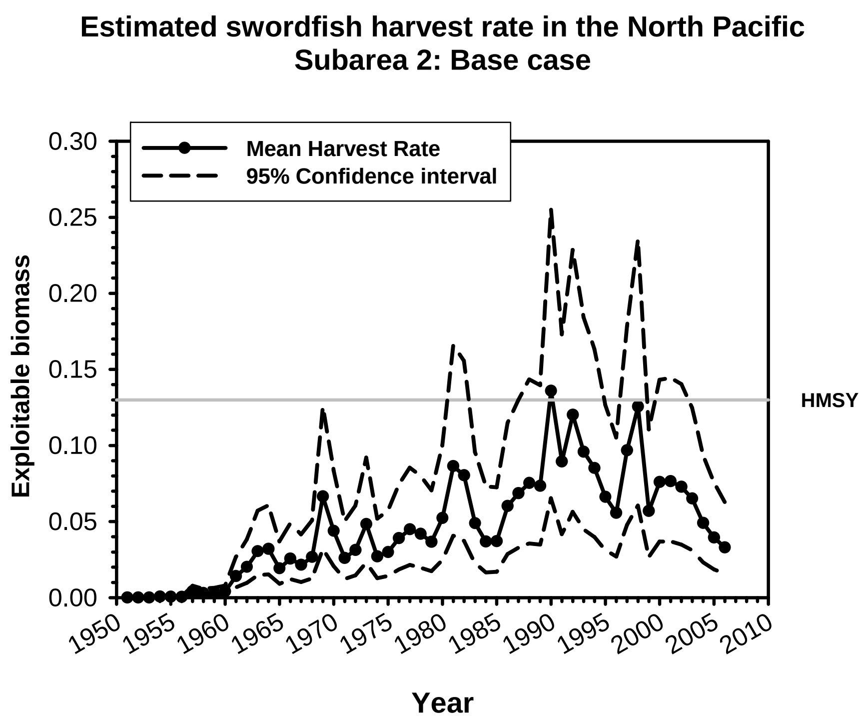


Figure 6.2.--Trends in exploitable biomass and exploitation rate of North Pacific swordfish in subarea 2 under the two-stock scenario, 1951–2006.

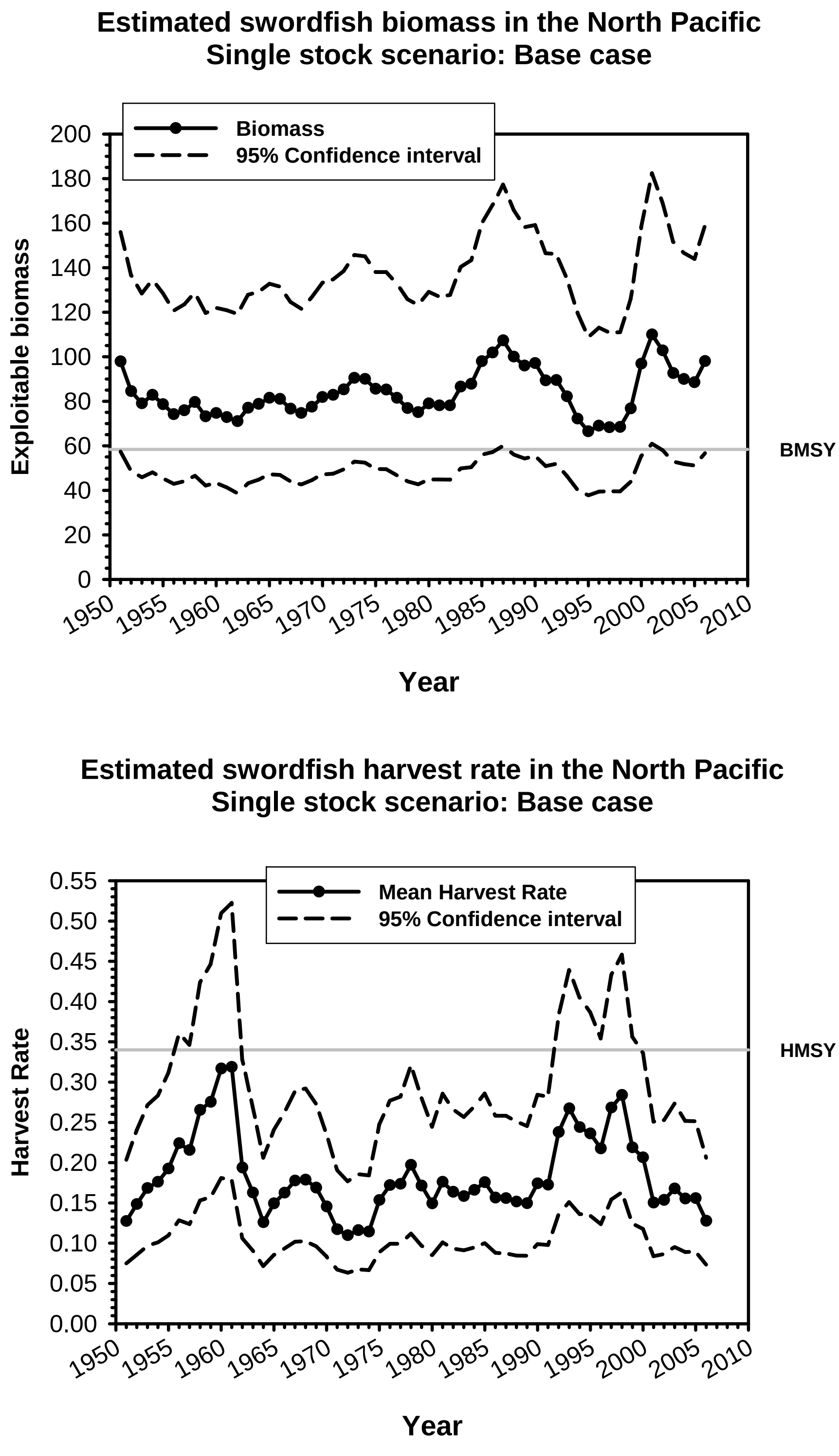


Figure 6.3.--Trends in exploitable biomass and exploitation rate of North Pacific swordfish under the single-stock scenario, 1951–2006.

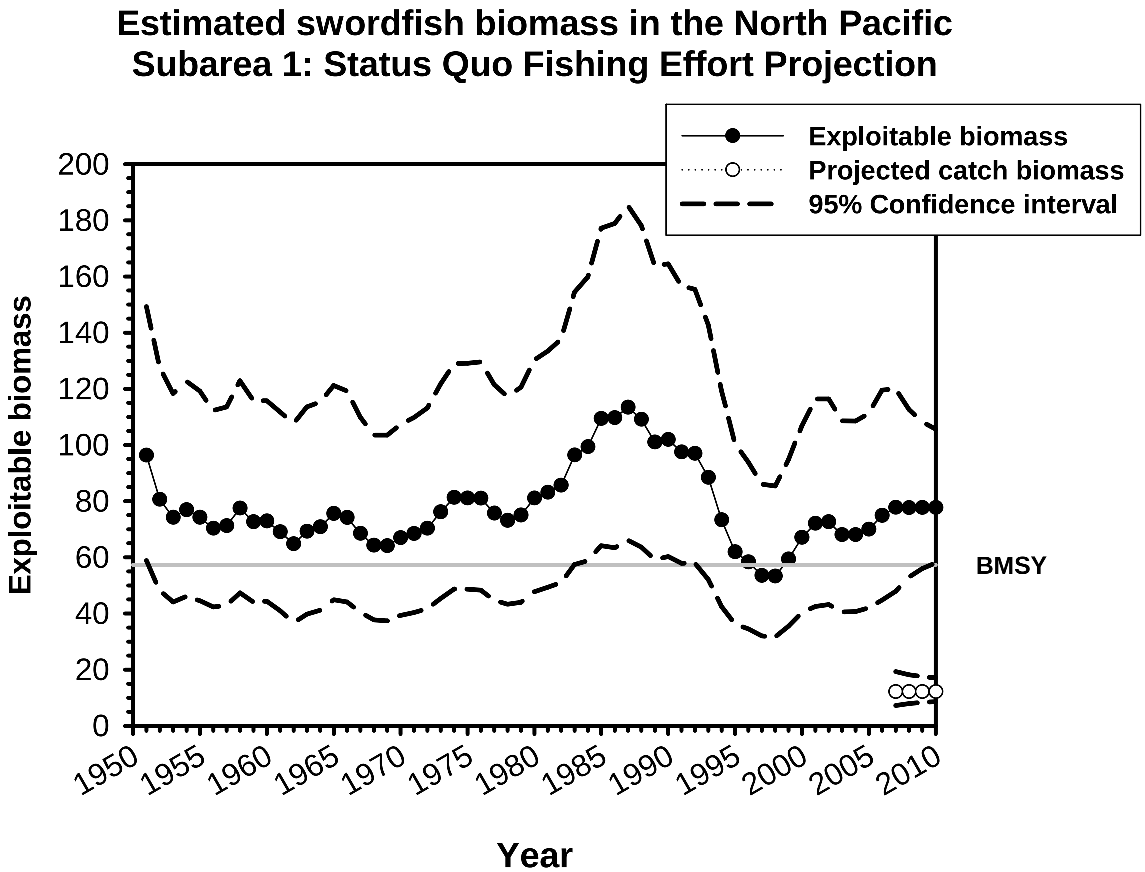


Figure 7.1.--Stochastic projections of swordfish exploitable biomass and catch biomass in subarea 1 during 2007–2010 assuming fishing effort has an iid stationary distribution.

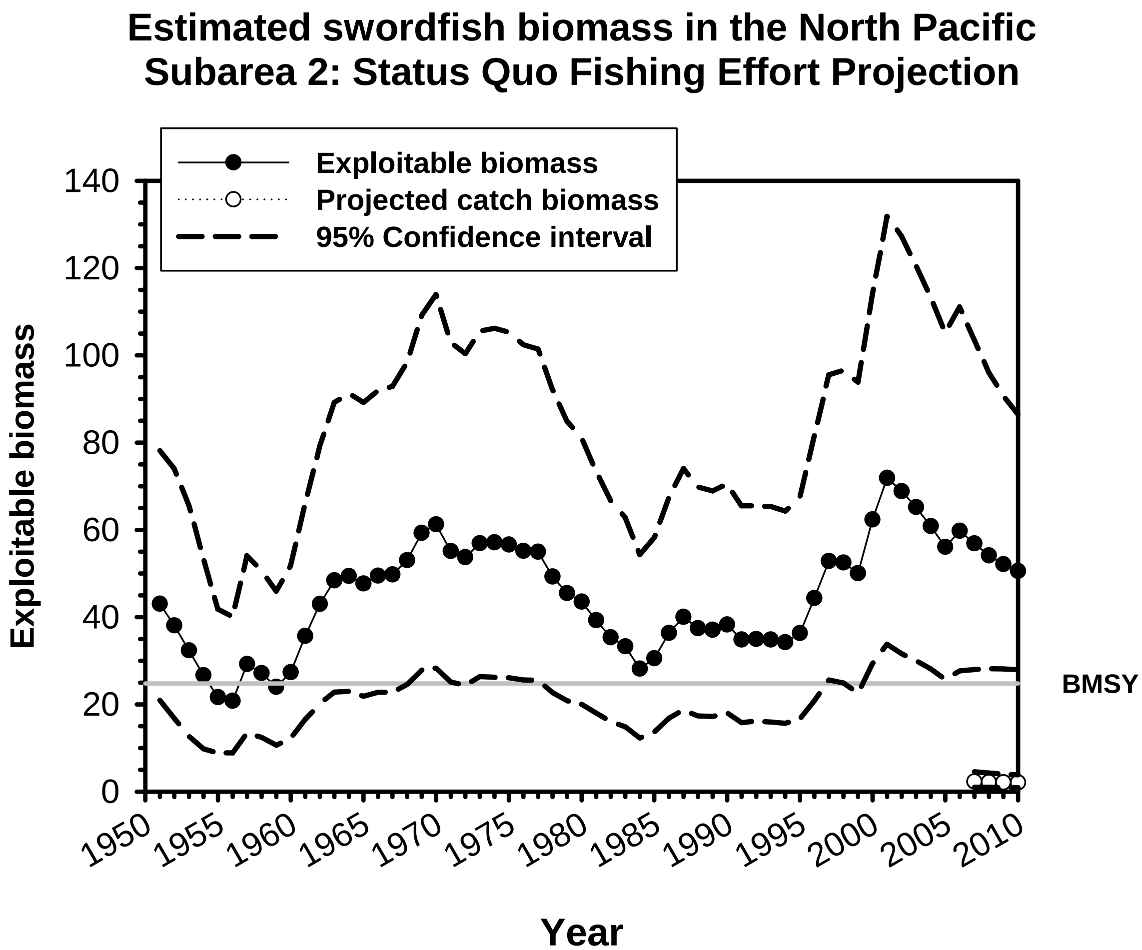


Figure 7.2.--Stochastic projections of swordfish exploitable biomass and catch biomass in subarea 2 during 2007–2010 assuming fishing effort has an iid stationary distribution.