Stock assessment of Western and Central North Pacific Ocean swordfish (*Xiphias gladius*) through 2012

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Abstract

We updated results of the stock assessment of the Western and Central North Pacific Ocean swordfish (WCNPO) stock conducted in 2009 by the ISC Billfish Working Group. The update consisted of running the Bayesian state-space surplus production model with new catch data that included revised estimates of WCNPO swordfish catches of Japan and Taiwan. The catch data from United States, Korea, and from other countries that derived from the WCPFC and IATTC category II database were also included. Relative abundance indices for swordfish consisted of standardized catch-per-unit effort (CPUE) for Japan, Taiwan, and USA longline fisheries. Four alternative production models that included various input CPUE indices and prior mean values were developed for the selection of base-case. Goodness-of-fit diagnostics were used to compare the fits of alternative model configurations. The Base-case joint-posterior distribution of intrinsic growth rate and carrying capacity were weakly correlated (coefficient-of-correlation = -0.24). The Base-case model indicated that biomass of swordfish in the WCNPO area was estimated to be 72,500 metric tons in 2012, which is well above the estimated B_{MSP} of 60,720 metric tons. The estimated harvest rate in 2012 was 0.14, which is lower than the estimated H_{MSP} of 0.25. We suggest that the WCNPO swordfish stock does not appear to have been heavily depleted or experienced overfishing during most of the assessment time horizon of 1951-2012. Sensitivity analyses showed that the model results were robust to changes in prior assumptions. Within-model retrospective analysis of recent 8 years of data suggested that there is no retrospective pattern in the biomass estimates.

1. 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 majority of catch has been taken by longline fishing vessels from Japan, Taiwan and the United States, which accounted for 95% of the total harvest in the North Pacific in 2010s, with the remaining catch taken by China, Korea, Mexico, and Spain.

Several stock structures have been proposed for Pacific swordfish (Alvarado Bremer et al., 2006; Ichinokawa and Brodziak, 2008). 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. It has been argued that the model fits and parameter estimates are sensitive to model structure.

ISC (2009) conducted the stock assessment of swordfish in the North Pacific Ocean by using the Bayesian surplus production model for the single-stock scenario and for the two- stock structure scenario (Figure 1), e.g., the two-stock scenario with Western and Central North Pacific Ocean (WCNPO) and Eastern Pacific Ocean (EPO) stocks. The previous assessment result suggested that the both swordfish stock biomass are above the biomass at which the maximum surplus production (*MSP*) is obtained and harvest rate is below the harvest rate required to achieve the *MSP* (ISC, 2009).

Based on general consensus that a two-stock scenario is likely, we present here an updated assessment of swordfish in the WCNPO area; assessment of the EPO swordfish stock is described in a separate working paper from this session by Yau et al. (2014). We applied a Bayesian statistical framework to estimate parameters of production models to assess the swordfish population in the WCNPO area using updated catch and effort through 2012. The Bayesian method provided direct estimates of parameter uncertainty that were straightforward to interpret and were appropriate for risk analyses. The objectives of this study are to update the ISC (2009) stock assessment for the WCNPO stock; to develop Bayesian posterior distributions for quantities of management interest using the Markov chain Monte Carlo (MCMC) algorithm; to examine the sensitivity of the results of the assessment to changes to its prior assumptions; and to conduct a retrospective analysis of stock assessment estimates.

2. MATERIALS AND METHODS

2.1 Fishery Data

2.1.1 Catch

Fishery catch data from 1951-2012 for assessing WCNPO swordfish were taken from the most recent summary of available fishery-dependent data (Kimoto and Yokawa, 2014; Ito and Childers, 2014). Commercial catch of swordfish caught by Japan, Taiwan, Korea, USA, and other countries in the WCNPO stock area were updated from the 2009 assessment (Table 1). More specifically, Japan, Taiwan, Korea, and the USA directly provided updated catch data, and swordfish catches for all other fishing countries in the WCNPO area were collected from WCPFC 2005-2012 and IATTC 2007-2012 category II data (Tagami et al., 2014). Japan included Japanese coastal, offshore, and distant-water longliners and other coastal gears. Taiwan included the distant water longline, offshore longline and costal fisheries and Korea included distant water longline fishery. For the IATTC data, the swordfish catch numbers in WCNPO area were converted to catch biomass (metric ton) by using the annual averaged weight that derived from the size-frequency data and the relationship between body biomass (W) and eye-fork-length (EFL) ($W=1.37\times10^{-5}EFL^{3.04}$, Uchiyama and Humphreys, 2007). For the WCPFC data, swordfish catch biomass were also separated by stock, the WCNPO stock included catch data from Belize, Cook Islands, China, Spain, Fiji, Federated States of Micronesia, Kiribati, Marshall Islands, Papua New Guinea, Senegal, Tuvalu, and Vanuatu.

2.1.2 Abundance indices

Estimates of standardized fishery-dependent CPUE of WCNPO swordfish were available for Japanese distant water and offshore longline fisheries, Taiwanese distant water longline fisheries, and the shallow-set sector of the Hawaii-based pelagic longline fishery (Table 2). More specifically, monthly aggregated dataset by 5x5 degree grids from 1952-1974 and those gear configurations from 1975 to 2012 were used in the CPUE standardization for Japanese distant water and offshore longline fisheries (Kimoto et al., 2014). Two standardized CPUE series were combined into a single period from 1952-2012 (n = 61) by using the average ratio of the standardized CPUEs for the overlapping period between 1975 and 1979. Alternative CPUE series without Japanese designated areas 8 and 9 was also provided by Kimoto et al. (2014).

For Taiwanese distant water longline fisheries, aggregated data by 5x5 degree grids, month, and gear configurations were used for CPUE standardization (Sun et al., 2014). Information about gear configuration is only available since 1995. It was noted that there is a change in targeting species and fishing ground of this fishery. Two standardized CPUE series for two separate periods of 1969 − 1999 (n = 25) with several missing values and 2000 − 2012 (n = 13) were developed.

Operational data in the shallow-set sector of the Hawaii-based pelagic longline fishery in 1995 − 2012 collected by fishery observers were used for CPUE standardization (Walsh and Brodziak, 2014). Swordfish is the target species in this sector, which underwent a closure between 2001 and 2004 due to excessive interactions with protected sea turtles. Because of this temporal gap, the analysis used data from 1995 − 2000 (n = 6) and 2005−2012 (n = 8).

2.2 Bayesian production model

Swordfish production models (see Appendix A) were formulated as Bayesian-state space models with explicit observation and process error terms (e.g., Meyer and Millar, 1999; Brodziak and Ishimura, 2009). We implemented the state-space models in WinBUGS (version 1.4.3, Lunn et al. 2000) via the R2WinBUGS package (Sturtz et al., 2005) in the statistical programming environment R (R Development Core Team 2008). Under the Bayesian paradigm, prior distributions are employed to quantify existing knowledge, or the lack thereof, of the likely value of each model parameter.

2.3 Prior distribution

The Bayesian analysis requires prior probability distributions for each of the model parameters. We follow the last assessment to use the same prior values of model parameters in this study except a least-informative prior for catchability. More specifically, we used lognormal distribution with coefficient of variation of 50% to describe the vague prior for both r and K (Table 3). The prior distribution for M was a gamma distribution with scale and shape parameters were equal with $\lambda = k = 2$. Therefore, the prior mean is equal to 1 and the CV is around 70%, which implied the production curve was centered on the symmetric Schaefer model as the default with adequate flexibility to estimate a non-symmetric production function if needed. Following Meyer and Millar (1999), we used inverse gamma prior for the process and observation error variances. The initial state of the stock was described as a proportion of carrying capacity (P_1=B_{1961}/K). To be consistent with the previous stock assessment P_1 was set to 0.9 with a CV of 10% based on an assumption that the swordfish population was lightly exploited following a cessation of fishing during World War II. However, an alternative model configuration that used a CV of 50% will be tested in the model selection section.

2.4 Convergence to posterior distribution

A critical issue in using MCMC methods is how to determine when random draws have converged to the posterior distribution. Convergence of the MCMC samples to the posterior distribution was checked by monitoring the trace and diagnosing the autocorrelation plot. Gelman and Rubin (1992) and Heidelberger and Welch (1983) diagnostics as implemented in the R language (R Development Core Team, 2008) and the CODA package (Best et al., 1995) were also examined. In this study, three chains were used. The model was run for 800,000 iterations, sampled with a thinning rate of 25 with a burn-in period of 200,000 for three chains for a total of 72,000 samples to generate the posterior distributions.

2.5 Diagnostics of model fitting

The predicted CPUE indices for each model were compared to the observed CPUE to determine model fit. Specifically, the root mean-squared error (RMSE) of the CPUE fit were used for the diagnostic of the model goodness of fit with lower RMSE indicating a better fit when comparing models with the same number of parameters. The goodness of fit among different models with same data structure was evaluated by Deviance information criterion (DIC) (Spiegelhalter et al., 2002). The standardized log-residuals from the CPUE fit were visually examined for time trends. The Shapiro-Wilk test (Shapiro and Wilk, 1965) was used to test the normality of the standardized log-residuals. The estimates of production model can be problematic when the data are not informative about whether the population has a high K and a low r or vice versa (Hilborn and Walters, 1992). The posterior correlation between model parameters was examined for the base-case model.

2.6 Model selection

Based on the preliminary analyses, four models differing in CPUE series and prior specification were explored. More specifically, Model 1 included updated catch and all CPUE indices which is a simple update with all available data. The prior distributions for model 1 were the same as were used in the previous WCNPO swordfish stock assessment except for a less informative prior for catchability. An alternative model configuration (Model 2) was developed which excluded the early-period Taiwanese CPUE (1969-1999). Model 3 that used the Japanese longline CPUE without the inclusion of catch-effort data from Japan-designated areas 8 and 9, along the border of the WCNPO and EPO swordfish stocks (Kimoto et al., 2014). These areas appeared to have different CPUE trends than adjacent areas in the WCNPO stock region. Model 4 used a CV of 50% for the lognormal prior distribution of the proportion of initial carrying capacity. In this context, it was thought that allowing for a more diffuse prior might provide more flexibility for the model to fit the initial stock biomass trends. To be consistent with the previous assessment, the relative coefficients of variations of CPUEs were all assumed to be 1 through time for each CPUE series for all models. After reviewing all runs for each model (see section 3.4), we adopt model 2 as the updated base-case assessment model to determine stock status and provide management advice for the WCNPO swordfish stock.

2.7 Sensitivity analysis

Sensitivity analyses were used to examine the effects of changing the assumed value of the input prior means for r, K, P_1, and M for WCNPO swordfish. The base-case model was run with the mean values for each of these priors changed by ±25% of their input value, e.g., 0.75*value and 1.25*value. Running the model with these high and low bounds would help identify which parameter was most important, and more importantly, whether assessment results were robust to a 25% change in an input prior.

2.8 Retrospective error

Retrospective analysis was conducted to examine the consistency among successive model estimates of population size, or related assessment variables obtained as new data are gathered. Within-model retrospective analysis which trims the most recent 8 years of data in successive model runs were used to examined changes in the estimates of exploitable biomass. Mohn's (1999) DR statistic was calculated as:

$$DR = \sum_{y=1}^{npeels} \frac{B_{Y-y,tip} - B_{Y-y,ref}}{B_{Y-y,ref}}$$

where B denotes exploitable biomass, y denotes year, *npeels* denotes the number of years that are dropped in successive fashion and the assessment rerun, Y is the last year in the full time series, *tip* denotes the terminal estimate from an assessment with a reduced time series, and *ref* denotes the assessment using the full time series.

3. RESULTS

3.1 Catch

The updated catch led to an increase of about 10% and 30% in the 1960 − 2000 and 2000 − 2009 reported swordfish catch biomass, respectively, compared to the 2009 assessment. Time-series of catches by fisheries was shown in Figure 2. During the 1950s, Japanese distant-water and offshore longline fisheries accounted for more than 80% of the annual swordfish harvests. The total reported annual catch of WCNPO swordfish peaked at 22,000 metric tons in 1960. In the following decade, however, these fleets rapidly expanded for targeting tunas, and swordfish catches rapidly decreased during the 1960s. During the 1970s, the average annual reported catch of swordfish in the WCNPO area was about 10,100 metric tons and the historical lowest catch of 6,800 metric tons occurred in 1972. The total swordfish catch slightly increased in the 1980s and reached a level of 15,800 metric tons in 1985 resulting from a few years of higher catch of Japanese distant-water and offshore longline fleets and other USA fisheries. The swordfish catches by Japanese distant-water and offshore longline fleets showed a declining trend since 1990. However, there was a steep increase in Hawaii-based longline catches during the early 1990s and total swordfish catch reached a high level of 19,200 metric tons, then declined to a level of 13,700 metric tons in 1996-1999. During the 2000s, the average annual reported catch of swordfish in the WCNPO was about 13,600 metric tons. After 2007, the total catches decreased significantly to around 10,000 metric tons and maintained at that level in 2011−2012. It should be noted a large fraction (25%) of the swordfish catch has been taken by the Taiwanese offshore longline and other fisheries during this period.

3.2 Abundance indices

Time-series of abundance indices available for this assessment was shown in Figure 3. Visual examination of the four CPUE indices suggested a similar trend of low CPUE in the 1970s, high CPUE in the early 1990s, and declining CPUE in the recent years among the indices used. Outliers in 1976, 1990, and 1995 were found in the Taiwanese distant water longline CPUE. The relative CV for Japanese distant water and offshore longline CPUE during 1952-1974 is larger than the CPUE values during 1975-2012. Higher relative CPUE was also in the earlier period of Taiwanese distant water longline (1969-1999) and the Hawaii longline during 1995-1999 (Table 2). There is no strong correlation ($|\rho| \geq 0.5$) among CPUE time series (Table 4). All CPUE indices were weakly or moderately positively correlated and had Pearson correlations ranging from -0.17 − 0.3, with the exception of the pairs of Japanese distant water and offshore longline (1952-2012) and Taiwanese distant water longline (2000-2012) (ρ = -0.06) and of Hawaii longline (1995-2012) and Taiwan DW longline (1969-1999) (ρ = -0.22).

3.3 Convergence of base-case model

The autocorrelation function plot indicated a thinning interval of 25 which was large enough to address potential autocorrelation in the MCMC runs. The visual inspection of trace plots of the major parameters showed the good mixing of the three chains (i.e., moving around the parameter space), also indicative of convergence of the MCMC chains. The Gelman and Rubin statistic for all parameters, including all variance terms, equaled 1, which indicated convergence of the Markov chains. Similarly, the Heidelberger and Welch test could not reject the hypothesis that the MCMC chains were stationary at the 95% confidence level for any of the parameters. Overall, these diagnostics indicated that the posterior distribution of the model parameters was adequately sampled with the MCMC simulations (see Appendix B for details)

3.4 Model fits to catch-per-unit-effort indices

The predicted CPUE indices for each model were compared to the observed CPUE to determine model fit. Plots of residual diagnostics by fishery for the base-case model were shown in Figure 4. Other candidate runs were provided in Appendix B. A summary table of residual patterns, normality test results, RMSE values and DIC values is also provided (Table 5). Several patterns were immediately apparent:

1) Models which included Taiwanese longline CPUE 1969-1999 had residuals which showed clear non-random temporal patterning in two Taiwanese longline CPUE indices (1969-1999 and 2000-2012) and the Hawaii longline CPUE. The Taiwanese longline CPUE 2000-2012 also failed the Shapiro-Wilk normality test (W = 0.82, $P < 0.05$).
2) The model fit with the alternative Japanese longline CPUE without Japan-designated areas 8 and 9 showed a poorer fit (RMSE = 2.716) and temporal residual pattern for the Hawaii CPUE compared to the model fit which included Japanese areas 8 and 9 (RMSE = 2.273).
3) A higher CV=50% for the prior distribution of P_1 did not produce an overall improvement to model fit to the CPUE indices and also showed a poorer fit (RMSE = 2.758) and temporal residual pattern for the Hawaii CPUE.

4) DIC were compared among models with the same data structure. Results indicated that the minimum value of DIC equal to -185.49 was achieved for the model 2 which was 8.48 and 2.90 units lower than the model 3 and model 4, respectively. Based on this information, we agreed to use model 2 as the base case model.

For the base-case model fits to CPUE, predicted Japanese longline CPUE fluctuated around the observed CPUE time series and the log-scale residuals had no time trend and were normally distributed (Figure 4). However, the Taiwanese longline CPUE fit had a pattern of consecutive negative residuals in the late-2000s. The log-scale residuals failed the normality test at significant level of 0.05 (W = 0.81, P = 0.001). Fits to the Hawaii longline CPUE appeared to have no trend in residuals and the log-scale residuals were normally distributed. Overall, the model fits to the WCNPO Pacific swordfish CPUE indicated that there was a good fit to the Japanese longline CPUE and a minor lack of fit to the Taiwanese longline CPUE.

3.5 Posterior correlation

Posterior estimates of r, K, M, P_1, catchability, B_{MSP}, H_{MSP}, *MSP* of base-case model were examined for correlations. For the major model parameters, the joint posterior for r and K has a “fried-egg” type appearance rather than a “banana” like appearance indicating that the typical strong correlation between r and K is not observed in this posterior (Figure 5). There is also a negative correlation between r and M (ρ = -0.69). There are considerable correlations between parameters of K, catchability, B_{MSP}, and H_{MSP}, whereas the correlations between the other parameters are low (Table 6).

3.6 Posterior estimates of model parameters

Plots of posterior densities of the parameters r, K, M, σ^2, τ^2, and P_1 were shown in Figure 6, together with their respective prior densities. Summaries of posterior quantiles of parameters and quantities of management interest were provided in Table 7. Similar to the log-normal priors, the marginal posteriors generally have a long right-hand tail. The marginal posterior for r has a median of about 0.54 (0.28-1.11 95% C.I.) and similar to the prior. Although both posterior and prior for *K* have a peak around 120 thousand metric tons, the posterior is less dispersed than the prior. The marginal posteriors for *M* and P_1 have median values of 0.89 (0.36-2.08 95% C.I.) and 0.84 (0.69-1.03 95% C.I.), respectively, and only slightly different to their priors. Although least informative priors are assigned to the process error and observation error variances, the posterior is less dispersed than the priors, which indicate the data reduced our uncertainty for each parameter. Furthermore, the observation error variance is greater than the process error variance. The marginal posteriors for *MSP*, H_{MSP}, and B_{MSP} were slightly right-tailed and the centered at the median values of 14.73 thousand metric tons, 0.25, and 59.52 thousand metric tons.

Parameter estimates from this 2014 update were generally similar to those from the 2009 assessment. The model parameter estimate of *K* that scaled with biomass was slightly higher in the current assessment (median 121.20 thousand metric tons) compared to the 2009 assessment (113 thousand metric tons). The parameter of *r* in this 2014 update did not differ substantially from the estimated value in 2009. The parameter *M* in this 2014 update also slightly differed from the value estimated in the 2009 assessment (Table 7). However, neither the 2014 estimate nor the 2009 estimate was significantly different from the value of 1 which indicated that the shape parameter was well-determined from the available data. Consequently, biomass to maximize surplus production (B_{MSP}) and maximum surplus production (*MSP*) from the 2014 assessment were all slightly greater than those values from the 2009 assessment.

Exploitable biomass of WCNPO swordfish has fluctuated at or above B_{MSP} throughout the assessment time horizon (Figure 7; Table 8). As expected, an inverse pattern of harvest rate fluctuated at or below H_{MSP} was observed. Trends in exploitable biomass and harvest rate from this 2014 update are very similar to those from the 2009 assessment. After several years of high catches (exploitation rates increased to fluctuate around H_{MSP} during 1956-1961), the biomass decreased to 69.05 thousand metric tons in 1962, and then fluctuated around 70 thousand metric tons. The harvest rate fluctuated around 50% of H_{MSP} from the mid-1960s to the late-1980s. In the meantime, the biomass increased to a peak around 1987 (2-fold higher than B_{MSP}). Due to the increase of swordfish catches during the 1990s (harvest rates increased to fluctuate about H_{MSP}), the biomass gradually declined to roughly B_{MSP} in 1996, and smaller than B_{MSP} in 1997 and 1998. The WCNPO swordfish catch showed a declining pattern since 2007, and harvest rates were fluctuating around 50% of H_{MSP}. For the recent 10 years, biomass was relatively stable and fluctuated above B_{MSP} (around 70 thousand metric tons). The probabilities of exploitable biomass being below B_{MSP} and harvest rate exceeding H_{MSP} in the final model year are 0.14 and 0, respectively. Kobe plot showed that the WCNPO swordfish stock does not appear to have been depleted (overfished) or experienced overfishing during most of the assessment time horizon of 1951-2012 (Figure 8).

3.7 Sensitivity analysis

The sensitivity analyses for the input prior means of the four parameters showed that the model results were robust to changes in the prior assumptions (Table 9). The trends of B/B_{MSP} are almost the same except for the model runs with lower or higher P_1 prior mean (Figures 9 and 10). However, the determination of stock status in 1997 and 1998 can be different depending on the sensitivity scenario. Lower r and P_1 prior mean would result in more pessimistic estimates of stock status in these years. A similar inverse pattern was found in the results for H/H_{MSP}. Overall, our CPUE data is informative and suggested that the prior assumptions were not driving the results of the base case WCNPO swordfish production model.

3.8 Retrospective analysis

Retrospective analyses show that the time-series of exploitable biomass estimate with the removal of most 8 years of data in successive model runs match very well with the full time series assessment (Figure 11). The Mohn's (1999) DR statistic is -0.06 for exploitable biomass, which suggested that there is no a consistent pattern of bias in the estimates of the terminal exploitable biomass.

Discussion

In our study, the Bayesian estimation approach provided a consistent theory for providing scientific advice that accounted for uncertainty in estimates of stock status relative to biological reference points. These benefits are considered to be important for effectively providing stock assessment results to fisheries managers and stakeholders. The probabilistic interpretation of stock status showed that it was very unlikely that the WCNPO swordfish population biomass was below B_{MSP} in 2012 (Prob($B_{2012} < B_{MSP}$)=0.14). Similarly, it was extremely unlikely that the swordfish population was being fished in excess of H_{MSP} in 2012 (Prob($H_{2012} > H_{MSP}$)=4.46x10^{-3}).

Although a single stock has generally been assumed for assessment purposes, fisheries stock assessment scientists recognized that not all exploited species fit easily into a unit stock definition. The choice of where to divide stocks and whether to treat them as independent can result in differing conclusions regarding population status (Beverton and Holt, 1957). ISC (2009) swordfish assessment indicated that the North Pacific swordfish population would be estimated to be a smaller- (lower *K*) and more productive stock (higher *r*) under the single-stock scenario than a combination of two stocks under the two-stock scenario. However, the aim of this study was to update the stock assessment for the swordfish in WCNPO area based on the two stocks scenario. We suggest that alternative swordfish stock structure hypotheses may need to be included in stock assessment to address the uncertainty associated with stock structure in the future.

Using a Bayesian estimation approach allowed us to make clear statements about the degree of confidence and uncertainty in estimated quantities. However, it is important to note that the choice of prior distributions can alter posterior estimates of stock status, especially when data quality is questionable (Booth and Quinn, 2006). Although the sensitivity analysis suggested that the prior mean were not driving the results of the base case, we suggest that it is important to explore the robustness of our stock assessment models to different prior distribution functions (e.g., uniform). We also suggest development of informative priors based on demographic analysis or priors that are consistent with data from other populations to reduce the estimation uncertainty (McAllister et al., 2001).

Swordfish are known as sexually dimorphic. For example, swordfish females mature later than males and the sex-ratio varies with length (DeMartini et al., 2000). These phenomena have implications for fishery selectivity and hence fishing-induced mortality. Therefore, we also recommend that further assessment work on WCNPO swordfish should consider more detailed biological data with sex-specific and age- or length-structured models and also provide the capacity to make stochastic catch projections under alternative harvest scenarios.

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Table 1. Swordfish catches (metric ton) in the Western and Central Pacific Ocean by fisheries, 1951-2012; “NA” indicates no effort or data not available, and “0” indicates less than 1 metric ton. “JPN” = Japan, “TWN” = Taiwan, “KOR” = Korea, “HW” = Hawaii, “DW” = Distant water, and “OS” = Offshore.

Year	JPN DW&OS longline	JPN other	TWN DW longline	TWN OS longline & other	KOR longline	HW longline	USA other	†Other	Total
1951	7245	4432	NA	NA	NA	NA	NA	NA	11677
1952	8888	2801	NA	NA	NA	NA	NA	NA	11689
1953	10794	1612	NA	NA	NA	NA	NA	NA	12405
1954	12543	1047	NA	NA	NA	NA	NA	NA	13591
1955	13050	1047	NA	NA	NA	NA	NA	NA	14097
1956	14590	890	NA	NA	NA	NA	NA	NA	15480
1957	14207	983	NA	NA	NA	NA	NA	NA	15190
1958	18510	1209	NA	NA	NA	NA	NA	NA	19719
1959	17181	1031	NA	518	NA	NA	NA	NA	18731
1960	19983	1342	NA	647	NA	NA	NA	NA	21972
1961	19398	1432	NA	391	NA	NA	NA	NA	21221
1962	9950	1508	NA	556	NA	NA	NA	NA	12014
1963	9644	922	NA	361	NA	NA	NA	NA	10926
1964	5594	1183	0	368	NA	NA	NA	NA	7145
1965	7506	2249	0	358	NA	NA	NA	NA	10113
1966	8809	1897	0	520	NA	NA	NA	NA	11226
1967	9845	1125	0	681	NA	NA	NA	NA	11651
1968	8067	1839	0	775	NA	NA	NA	NA	10681
1969	7508	1920	0	850	NA	NA	NA	NA	10278
1970	5280	2223	0	909	NA	5	622	NA	9039
1971	5437	909	0	995	0	1	102	NA	7444
1972	4814	891	0	873	0	0	175	NA	6753
1973	4833	1307	0	979	0	0	403	NA	7522
1974	4791	2193	0	1016	0	0	428	NA	8428
1975	5835	3575	11	1052	0	0	570	NA	11043
1976	6386	4747	10	807	0	0	55	NA	12005
1977	7452	3505	3	683	165	17	337	NA	12162
1978	7532	3769	0	558	53	9	1712	NA	13633
1979	8168	2246	7	694	NA	7	386	NA	11508
1980	5655	3038	11	679	47	5	788	NA	10223

Continued

1981	6638	2774	1	681	NA	3	746	NA	10843
1982	5312	2392	1	904	39	5	1111	NA	9764
1983	7318	2239	0	949	9	5	1758	NA	12278
1984	7001	2458	0	997	42	3	2838	NA	13339
1985	9114	2402	0	825	22	2	3399	NA	15764
1986	8160	2480	0	667	7	2	2469	NA	13785
1987	8695	2054	1	1518	35	24	1795	NA	14122
1988	8144	2112	0	1040	21	24	1638	NA	12979
1989	5942	2741	4	1529	30	218	1361	NA	11825
1990	5390	1909	5	1463	41	2436	1238	NA	12482
1991	4377	1483	10	1570	3	4508	1035	NA	12986
1992	6911	2471	2	1716	5	5700	1540	NA	18345
1993	7955	2043	58	1484	11	5909	1768	NA	19228
1994	7015	2127	0	1374	49	3176	1604	NA	15345
1995	6005	2412	71	1360	7	2713	1165	NA	13733
1996	6260	2141	10	733	11	2502	1203	NA	12860
1997	6250	1992	20	1419	69	2881	1315	NA	13946
1998	5590	2207	22	1219	100	3263	1416	NA	13817
1999	5292	2241	63	1446	102	3100	1943	NA	14187
2000	5398	2480	64	3476	147	2949	2630	NA	17144
2001	5194	1915	121	3903	255	220	2181	NA	13789
2002	5199	2370	155	3793	284	204	1715	NA	13720
2003	4794	2442	144	3554	247	147	2156	NA	13484
2004	4939	2834	502	3327	300	213	1200	NA	13315
2005	5054	2777	269	3505	339	1622	307	297	14170
2006	5805	2897	203	3891	389	1211	523	133	15051
2007	5916	3337	191	3744	170	1735	555	151	15799
2008	3979	2960	162	3443	351	2014	478	244	13631
2009	3729	2710	147	3222	280	1817	306	163	12375
2010	3660	1918	231	2324	278	1676	119	463	10670
2011	2430	1320	366	2999	256	1623	237	226	9456
2012	2446	1680	576	3049	245	1418	110	338	9863

†catch data from Belize, Cook Islands, China, Spain, Fiji, Federated States of Micronesia, Kiribati, Marshall Islands, Papua New Guinea, Senegal, Tuvalu, Vanuatu

Table 2. Swordfish standardized CPUE in Western and Central Pacific Ocean stock by fisheries, 1951-2012. “NA” indicates no effort or data not available. “JPN” = Japan, “TWN” = Taiwan, “HW” = Hawaii, “DW” = Distant water, and “OS” = Offshore.

Year	JPN DW&OS longline		TWN DW longline series I		TWN DW longline series II		HW longline	
	CPUE	Relative CV	CPUE	Relative CV	CPUE	Relative CV	CPUE	Relative CV
1952	0.20	1.79						
1953	0.17	1.78						
1954	0.24	1.78						
1955	0.21	1.76						
1956	0.17	1.75						
1957	0.18	1.75						
1958	0.25	1.75						
1959	0.19	1.74						
1960	0.21	1.74						
1961	0.20	1.74						
1962	0.19	1.73						
1963	0.22	1.73						
1964	0.20	1.73						
1965	0.22	1.72						
1966	0.22	1.72						
1967	0.19	1.71						
1968	0.16	1.72						
1969	0.18	1.72	0.06	3.74				
1970	0.19	1.71	0.05	5.62				
1971	0.19	1.72	0.05	2.47				
1972	0.18	1.73	0.05	2.62				
1973	0.21	1.73	0.04	9.46				
1974	0.24	1.72	0.05	1.24				
1975	0.21	1.05	0.06	1.54				
1976	0.24	1.02	0.14	1.72				
1977	0.21	1.01	0.06	1.54				
1978	0.18	1.00						
1979	0.20	1.00	0.08	1.30				
1980	0.25	1.01	0.06	1.37				
1981	0.23	1.00	0.06	1.19				

Continued

1982	0.22	1.01	0.06	1.88				
1983	0.30	1.01	0.05	3.82				
1984	0.27	1.00	0.06	9.24				
1985	0.37	1.02						
1986	0.35	1.01						
1987	0.39	1.01	0.07	2.76				
1988	0.36	1.00						
1989	0.28	1.01	0.11	1.69				
1990	0.32	1.02	0.16	2.85				
1991	0.27	1.01	0.14	2.02				
1992	0.30	1.02	0.11	4.43				
1993	0.29	1.02						
1994	0.23	1.01						
1995	0.20	1.01	0.16	1.14			8.33	2.12
1996	0.20	1.01	0.08	1.00			8.54	2.31
1997	0.14	1.02	0.07	1.02			9.18	2.05
1998	0.14	1.02	0.06	1.19			8.20	2.11
1999	0.17	1.01	0.08	1.04			11.20	1.46
2000	0.20	1.02			0.14	1.21	10.61	2.93
2001	0.24	1.04			0.17	1.15		
2002	0.21	1.03			0.24	1.18		
2003	0.16	1.01			0.19	1.11		
2004	0.17	1.04			0.27	1.00		
2005	0.18	1.04			0.17	1.00	13.33	1.14
2006	0.22	1.03			0.17	1.01	16.32	1.02
2007	0.18	1.05			0.16	1.03	13.83	1.18
2008	0.17	1.05			0.16	1.03	13.53	1.09
2009	0.20	1.07			0.16	1.06	10.90	1.23
2010	0.21	1.10			0.18	1.07	9.23	1.23
2011	0.17	1.08			0.16	1.04	11.70	1.00
2012	0.20	1.16			0.17	1.10	11.18	1.09

Table 3. Summary of specified priors for Bayesian state-space model.

Parameter	Description	Prior
r	Intrinsic growth rate (yr^{-1})	$r \sim \log N\left(\log(0.5)-\frac{\pm_r^2}{2},\pm_r^2\right);\ CV_r=0.5$
K	Carrying capacity (1000 mt)	$K \sim \log N\left(\log(150)-\frac{\pm_K^2}{2},\pm_K^2\right);\ CV_K=0.5$
M	Production shape	$M \sim Gamma(2,2)$
q	Catchability	$1/q \sim Gamma(0.01,0.01)$
²^2	Observation error variance	$1/$²$^2 \sim Gamma(2,0.45)$
P_1	Initial condition (B_1/K)	$P_1 \sim \log N\left(\log(0.9)-\frac{\pm_{P_1}^2}{2},\pm_{P_1}^2\right);\ CV_{P_1}=0.1$
$\pm^2$	Process error variance	$1/\pm^2 \sim Gamma(4,0.1)$

$CV_{-}=\left(\exp\left(\pm_{-}^2\right)-1\right)^{1/2}$

Table 4. Correlation matrix of various CPUE indices. Lower diagonal values denote correlation coefficient and upper diagonal values denote number of overlapped years. “JPN” = Japan, “TWN” = Taiwan, “HW” = Hawaii, “DW” = Distant water, and “OS” = Offshore.

	JPN DW&OS longline 1952-2012	TW DW longline 1969-1999	TW DW longline 2000-2012	HW longline 1995-2012
JPN DW&OS longline 1952-2012	1	25	13	14
TW DW longline 1969-1999	0.30	1	0	5
TW DW longline 2000-2012	-0.06	NA	1	9
HW longline 1995-2012	0.28	-0.22	0.17	1

Table 5. Diagnostics of model fitting for base-case model selection. Indices with time trends are the CPUE indices with obvious time trends apparent via gross visual examination. Indices with non-normality are the CPUE indices with a Shapiro–Wilk test *P*-value < 0.05. DIC is the deviance information criteria. S1= JPN DW&OS longline 1952-2012, S2=TWN DW longline 1969-1999, S3=TWN DW longline 2000-2012, S4=HW longline 1995-2012.

Run	Indices with time trends	Indices with non-normality	Root mean square error				DIC value
			S1	S2	S3	S4	
Model 1	S2,S3,S4	S3 (P<0.5)	0.034	0.033	0.038	2.399	-284.52
Model 2 (base-case)		S3 (P<0.5)	0.033	NA	0.038	2.273	-185.49
Model 3	S4		0.035	NA	0.039	2.716	-177.01
Model 4	S4		0.033	NA	0.039	2.758	-182.58

Table 6. Correlation matrix of posterior estimates for the base-case model. The background color denotes the contour of coefficients of correlations.

	r	K	M	P_1	q_{JPN}	q_{TWN}	q_{HW}	B_{MSP}	H_{MSP}	MSP
r										
K	-0.25									
M	-0.67	-0.25								
P_1	0.03	-0.11	0.07							
q_{JPN}	0.23	-0.86	0.17	0.02						
q_{TWN}	0.20	-0.78	0.15	0.02	0.90					
q_{HW}	0.21	-0.79	0.15	0.02	0.91	0.86				
B_{MSP}	-0.56	0.91	0.16	-0.08	-0.81	-0.73	-0.75			
H_{MSP}	0.68	-0.74	-0.15	0.12	0.60	0.52	0.54	-0.81		
MSP	0.32	0.05	-0.04	0.09	-0.23	-0.24	-0.23	0.03	0.50	

Table 7. Summary of posterior quantiles of parameters for the base-case production model for the swordfish in the Western and Central Pacific Ocean.

Parameter	Mean	SD	2.50%	Median	97.50%	2009 Assessment (median)
Intrinsic rate of pop. growth (r)	0.58	0.22	0.28	0.54	1.11	0.54
Carrying capacity (K; 1000 mt)	123.70	24.63	82.79	121.20	178.50	113
Production shape parameter (M)	0.98	0.45	0.36	0.89	2.08	0.93
Process error variance (σ^2)	0.02	0.00	0.01	0.02	0.03	0.02
JPN longline obs. error variance ($2\,{}^{2}_{JPN}$)	0.04	0.01	0.02	0.03	0.05	0.04
TWN longline obs. error variance ($2\,{}^{2}_{TWN}$)	0.09	0.04	0.04	0.09	0.19	0.14
HW longline obs. error variance ($2\,{}^{2}_{HW}$)	0.09	0.04	0.04	0.08	0.19	0.13
P_1 (B_{1951}/K)	0.85	0.09	0.69	0.84	1.03	0.85
JPN longline catchability (q_{JPN})	2.82E-03	6.18E-04	1.79E-03	2.76E-03	4.20E-03	2.97E-03
TWN longline catchability (q_{TWN})	2.67E-03	6.21E-04	1.65E-03	2.60E-03	4.07E-03	2.79E-03
HW longline catchability (q_{HW})	0.17	0.04	0.10	0.16	0.26	0.20
Biomass in 1951 (B_{1951}; 1000 mt)	104.60	22.37	67.86	102.20	155.30	96.35
Biomass in 2012 (B_{2012}; 1000 mt)	72.50	17.47	44.51	70.44	112.20	72.93
Harvest rate in 1951 (H_{1951})	0.12	0.02	0.08	0.11	0.17	0.12
Harvest rate in 2012 (H_{2012})	0.14	0.03	0.09	0.14	0.22	0.14
Max. surplus production (MSP; 1000 tons)	14.92	1.82	11.88	14.73	19.08	14.23
Biomass giving MSP (B_{MSP}; 1000 tons)	60.72	11.79	41.11	59.52	86.90	55.94
Harvest rate giving MSP (H_{MSP})	0.25	0.06	0.16	0.25	0.38	0.26
Probability that B_{2012} being below B_{MSP} (Prob($B_{2012} < B_{MSP}$))	0.14	0.35	0	0	1.00	0
Probability that H2012 exceeds H_{MSP} (Prob($H_{2012} > H_{MSP}$))	4.46E-03	6.66E-02	0	0	0	0

Table 8. Estimates of exploitable biomass (1000 metric ton) and mean harvest rate derived from the base-case production model for the swordfish in the Western and Central North Pacific Ocean.

Year	Exploitable biomass				Harvest rate			
	Mean	median	2.5%	97.5%	Mean	median	2.5%	97.5%
1951	104.60	102.20	67.86	155.30	0.12	0.11	0.08	0.17
1952	87.01	84.76	53.66	133.10	0.14	0.14	0.09	0.22
1953	79.61	77.42	48.64	123.40	0.16	0.16	0.10	0.26
1954	81.83	79.52	50.04	126.70	0.18	0.17	0.11	0.27
1955	78.77	76.46	48.22	122.10	0.19	0.18	0.12	0.29
1956	74.86	72.70	45.86	116.50	0.22	0.21	0.13	0.34
1957	75.76	73.48	46.48	117.90	0.21	0.21	0.13	0.33
1958	81.88	79.44	50.88	126.50	0.25	0.25	0.16	0.39
1959	76.98	74.67	47.47	119.30	0.26	0.25	0.16	0.39
1960	77.21	74.92	47.85	119.90	0.30	0.29	0.18	0.46
1961	73.29	70.91	44.50	115.30	0.31	0.30	0.18	0.48
1962	68.93	66.66	40.07	110.80	0.19	0.18	0.11	0.30
1963	73.50	71.20	43.42	116.80	0.16	0.15	0.09	0.25
1964	74.68	72.44	44.36	117.70	0.10	0.10	0.06	0.16
1965	80.05	77.69	48.71	124.90	0.13	0.13	0.08	0.21
1966	78.82	76.57	47.99	122.50	0.15	0.15	0.09	0.23
1967	72.97	70.85	44.19	114.10	0.17	0.16	0.10	0.26
1968	68.54	66.51	41.08	107.50	0.17	0.16	0.10	0.26
1969	68.85	66.78	41.23	108.20	0.16	0.15	0.09	0.25
1970	70.63	68.50	42.47	110.80	0.14	0.13	0.08	0.21
1971	72.23	70.12	43.60	112.80	0.11	0.11	0.07	0.17
1972	74.62	72.48	45.27	116.40	0.10	0.09	0.06	0.15
1973	81.01	78.73	49.71	125.50	0.10	0.10	0.06	0.15
1974	86.16	83.75	53.17	133.00	0.10	0.10	0.06	0.16
1975	85.99	83.64	53.06	132.70	0.14	0.13	0.08	0.21
1976	85.85	83.36	52.62	133.00	0.15	0.14	0.09	0.23
1977	81.04	78.78	49.45	125.90	0.16	0.15	0.10	0.25
1978	77.99	75.69	47.39	121.60	0.19	0.18	0.11	0.29
1979	79.28	76.92	47.65	124.40	0.15	0.15	0.09	0.24
1980	85.73	83.21	51.90	134.30	0.13	0.12	0.08	0.20
1981	88.18	85.67	53.49	137.90	0.13	0.13	0.08	0.20
1982	91.10	88.36	55.19	142.70	0.11	0.11	0.07	0.18
1983	102.70	99.67	62.85	159.20	0.13	0.12	0.08	0.20
1984	106.30	103.10	64.33	165.70	0.13	0.13	0.08	0.21
1985	116.90	113.30	70.68	183.80	0.14	0.14	0.09	0.22
1986	117.70	114.00	69.76	186.90	0.12	0.12	0.07	0.20
1987	121.30	117.40	71.88	191.80	0.12	0.12	0.07	0.20

Continued

1988	116.70	113.10	69.49	184.80	0.12	0.11	0.07	0.19
1989	108.00	104.70	64.43	170.30	0.12	0.11	0.07	0.18
1990	108.70	105.50	65.89	169.80	0.12	0.12	0.07	0.19
1991	104.10	101.00	63.33	162.70	0.13	0.13	0.08	0.21
1992	103.80	100.80	63.69	161.70	0.19	0.18	0.11	0.29
1993	94.69	91.77	57.20	148.60	0.22	0.21	0.13	0.34
1994	80.19	77.70	47.79	127.00	0.20	0.20	0.12	0.32
1995	70.20	67.98	42.07	110.30	0.21	0.20	0.12	0.33
1996	65.65	63.72	39.74	102.60	0.21	0.20	0.13	0.32
1997	60.86	59.09	37.04	94.96	0.24	0.24	0.15	0.38
1998	60.20	58.42	36.72	93.78	0.24	0.24	0.15	0.38
1999	65.18	63.35	39.97	100.90	0.23	0.22	0.14	0.36
2000	69.82	67.84	43.34	107.80	0.26	0.25	0.16	0.40
2001	74.02	71.85	45.14	115.00	0.20	0.19	0.12	0.31
2002	75.47	73.29	46.18	117.10	0.19	0.19	0.12	0.30
2003	71.61	69.56	43.87	111.40	0.20	0.19	0.12	0.31
2004	73.37	71.22	44.92	114.20	0.19	0.19	0.12	0.30
2005	73.86	71.76	45.66	114.30	0.20	0.20	0.12	0.31
2006	76.32	74.09	47.17	117.80	0.21	0.20	0.13	0.32
2007	72.29	70.18	44.42	111.90	0.23	0.23	0.14	0.36
2008	68.62	66.62	41.86	106.90	0.21	0.20	0.13	0.33
2009	68.77	66.74	41.88	107.00	0.19	0.19	0.12	0.30
2010	68.97	66.98	41.98	107.40	0.16	0.16	0.10	0.25
2011	68.56	66.57	41.97	106.70	0.15	0.14	0.09	0.23
2012	72.50	70.44	44.51	112.20	0.14	0.14	0.09	0.22

Table 9. Effects of high (+25%) and low (-25%) changes in prior means on model parameters including maximum surplus production yield (*MSP*), exploitable biomass to produce *MSP* (B_{MSP}), and harvest rate to produce *MSP* (H_{MSP}).

Parameter	Base-case		1.25*r		0.75*r		1.25*K		0.75*K		1.25*P_1		0.75*P_1		1.25*M		0.75*M	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD
r	0.58	0.22	0.66	0.26	0.49	0.18	0.57	0.21	0.59	0.22	0.58	0.22	0.56	0.21	0.55	0.21	0.62	0.23
K	123.66	24.63	121.30	24.71	127.08	25.62	128.01	25.74	116.55	23.09	113.54	23.74	129.02	26.34	122.22	24.73	125.00	25.07
M	0.98	0.45	0.87	0.42	1.13	0.50	0.97	0.46	1.01	0.46	1.15	0.57	0.94	0.45	1.07	0.51	0.87	0.38
P_1	0.85	0.09	0.85	0.09	0.85	0.09	0.85	0.09	0.85	0.09	1.09	0.13	0.65	0.06	0.85	0.09	0.85	0.08
B_{MSP}	60.72	11.79	58.26	11.37	64.16	12.73	62.71	12.24	57.64	11.14	57.34	11.51	62.88	12.41	60.97	12.07	60.12	11.72
B_{1951}	104.60	22.37	102.80	22.49	107.40	23.13	108.10	23.30	98.88	21.08	123.10	26.40	83.17	18.37	103.60	22.44	105.50	22.54
B_{1951}/B_{MSP}	1.73	0.22	1.77	0.22	1.68	0.21	1.73	0.22	1.72	0.22	2.16	0.27	1.33	0.16	1.71	0.22	1.76	0.22
B_{2012}	72.50	17.47	71.49	17.59	74.19	17.95	75.02	18.22	68.58	16.36	69.24	17.64	70.89	16.69	71.88	17.45	72.92	17.44
B_{2012}/B_{MSP}	1.20	0.19	1.23	0.19	1.16	0.18	1.20	0.19	1.19	0.19	1.21	0.20	1.13	0.18	1.18	0.19	1.22	0.19
H_{MSP}	0.25	0.06	0.27	0.06	0.24	0.05	0.25	0.06	0.27	0.06	0.28	0.06	0.24	0.05	0.25	0.06	0.26	0.06
H_{1951}	0.12	0.02	0.12	0.03	0.11	0.02	0.11	0.02	0.12	0.03	0.10	0.02	0.15	0.03	0.12	0.03	0.12	0.02
H_{1951}/H_{MSP}	0.47	0.08	0.45	0.08	0.49	0.09	0.47	0.08	0.47	0.08	0.36	0.07	0.62	0.10	0.47	0.09	0.46	0.08
H_{2012}	0.14	0.03	0.15	0.04	0.14	0.03	0.14	0.03	0.15	0.04	0.15	0.04	0.15	0.03	0.15	0.03	0.14	0.03
H_{2012}/H_{MSP}	0.58	0.13	0.56	0.13	0.61	0.14	0.58	0.13	0.58	0.13	0.56	0.13	0.63	0.14	0.59	0.13	0.57	0.13
MSP	14.92	1.82	15.13	1.86	14.67	1.77	14.93	1.86	14.89	1.75	15.32	1.89	14.53	1.61	14.91	1.79	14.91	1.80

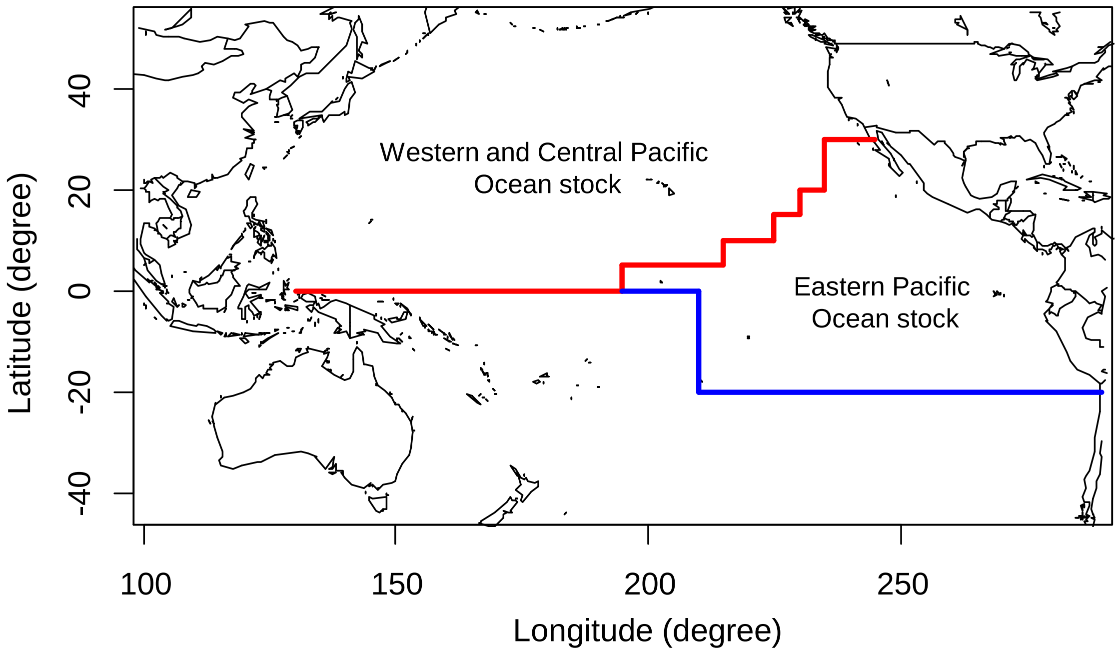

Figure 1. Spatial definition of management units for North Pacific swordfish stock assessments conducted by the ISC Billfish Working Group in 2009 with stocks in the Western and Central Pacific Ocean (WCNPO stock) and in the Eastern Pacific Ocean (EPO stock).

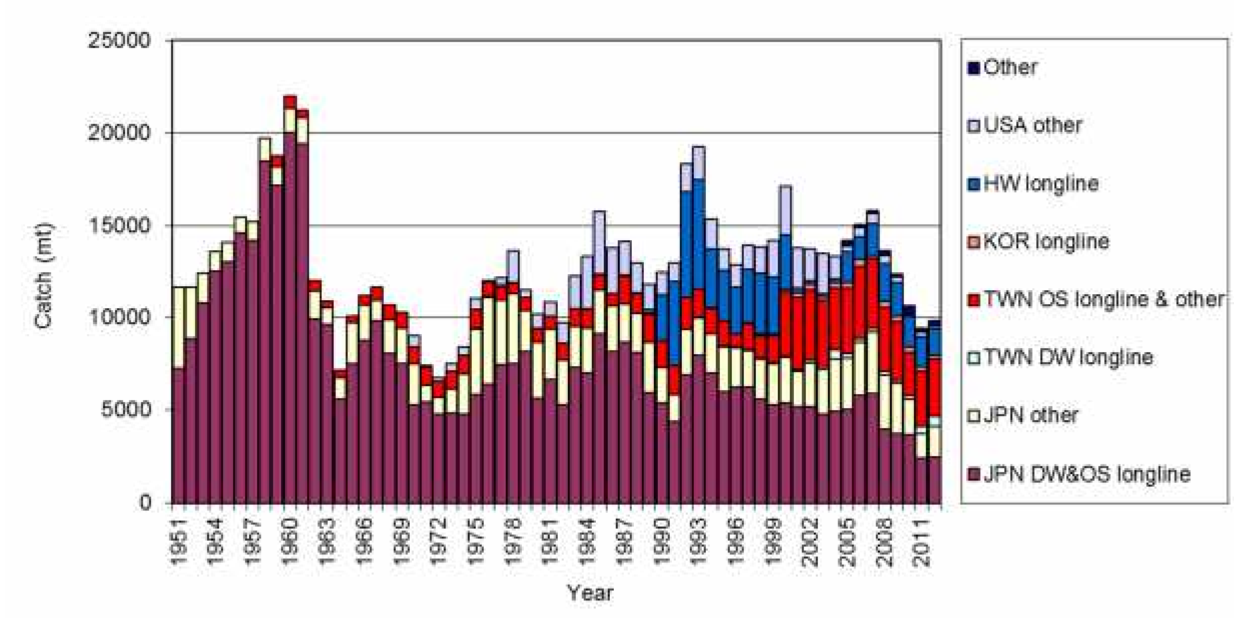

Figure 2. Time-series of catch (metric ton) of Western and Central North Pacific Ocean swordfish by major fishery. “JPN” = Japan, “TWN” = Taiwan, “KOR” = Korea, “HW” = Hawaii, “DW” = Distant water, and “OS” = Offshore.

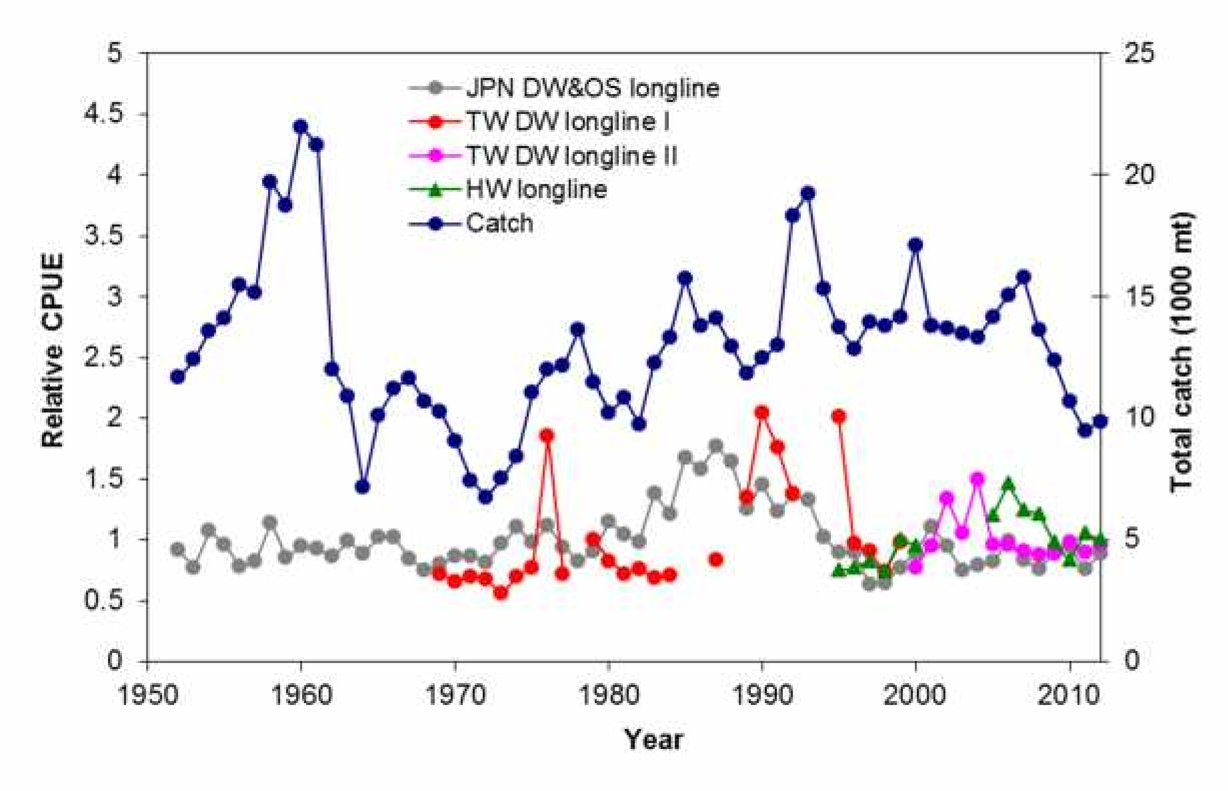

Figure 3. Western and Central North Pacific Ocean swordfish catch biomass and four relative CPUE indices from Japan, Taiwan and Hawaii longline fisheries. “JPN” = Japan, “TW” = Taiwan, “HW” = Hawaii, “DW” = Distant water, and “OS” = Offshore.

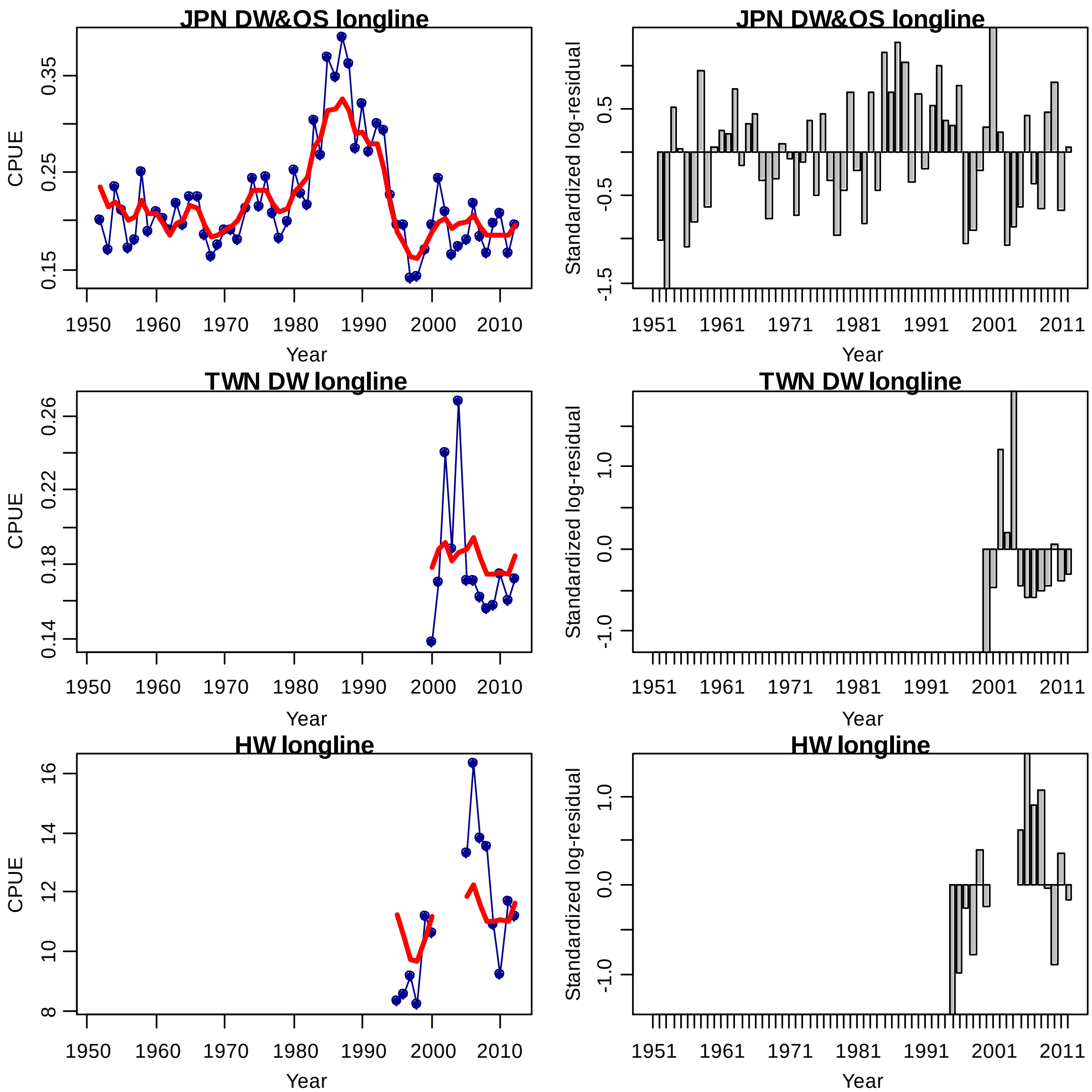

Figure 4. Time-series of observed (blue circle line) and predicted (red solid line) catch per unit effort (CPUE) of Western and Central North Pacific Ocean swordfish (left panels) and standardized log-residuals (right panels) for the base-case production model. “JPN” = Japan, “TW” = Taiwan, “HW” = Hawaii, “DW” = Distant water, and “OS” = Offshore.

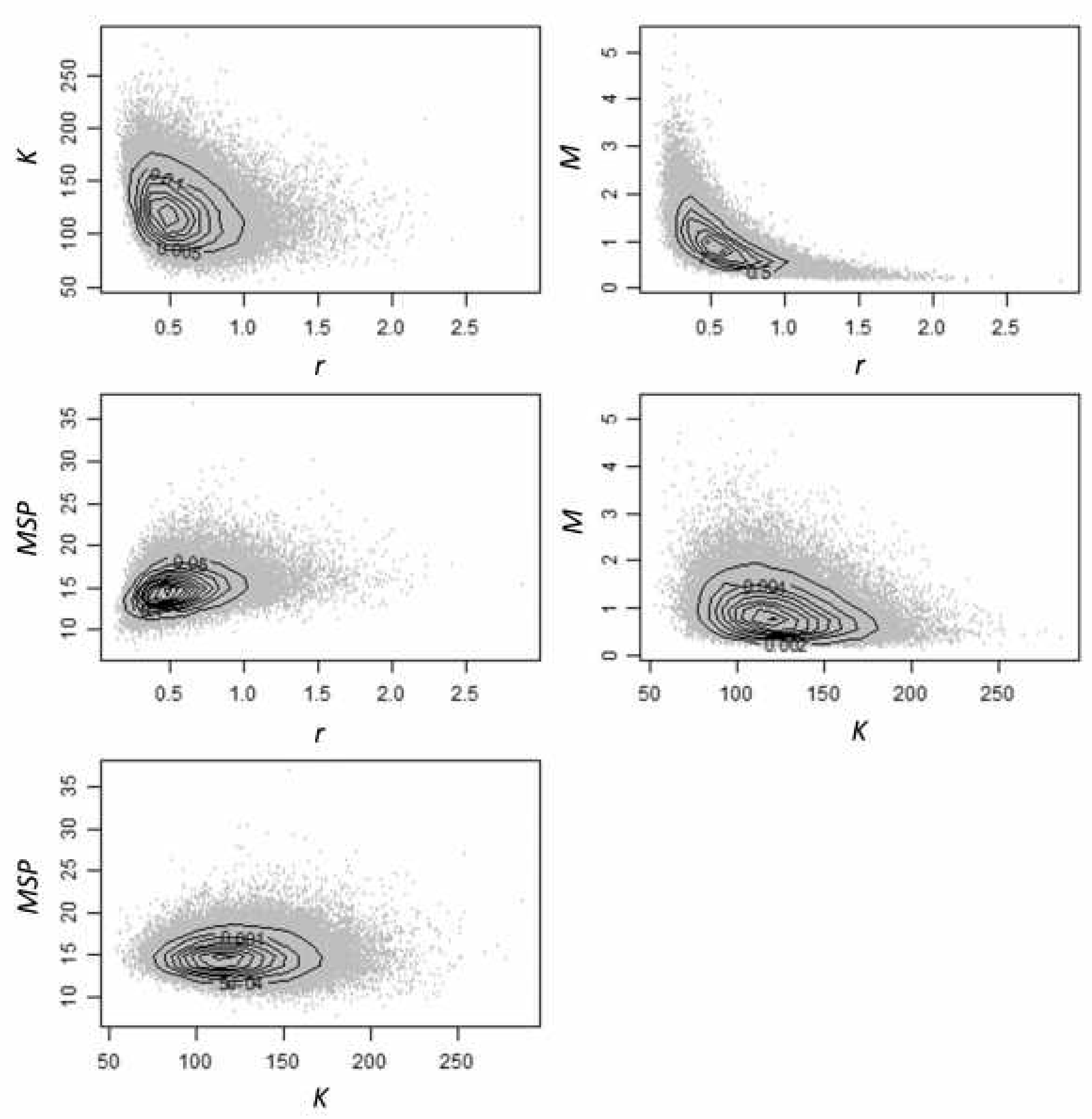

Figure 5. Joint-posterior plots of main model parameters for the base-case production model for the swordfish in the Western and Central North Pacific Ocean.

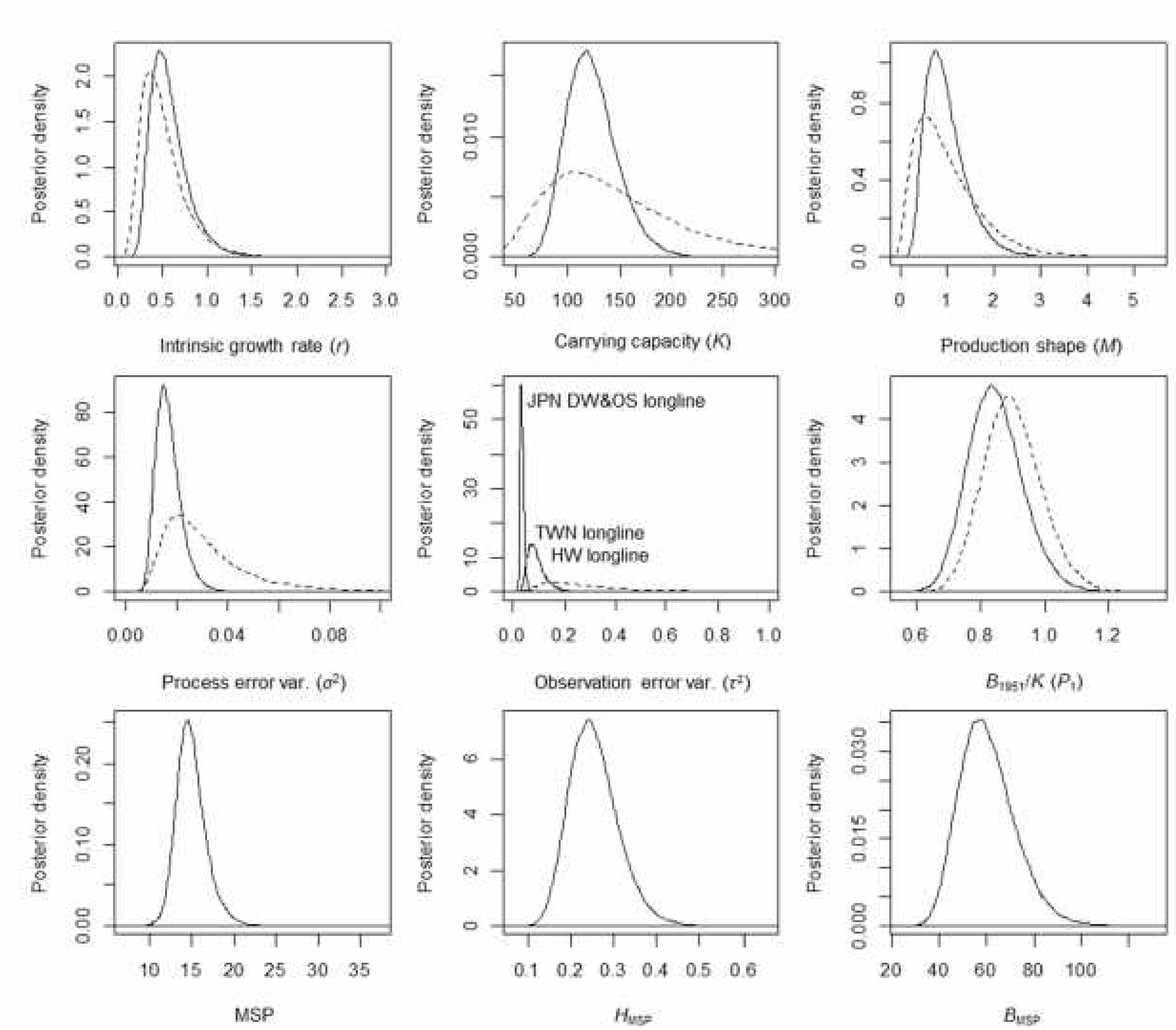

Figure 6. Kernel density estimates (solid lines) of the posterior distribution of various model and management parameters for the base-case production model for the swordfish in the Western and Central Pacific Ocean. Proper prior densities are given by the dotted lines.

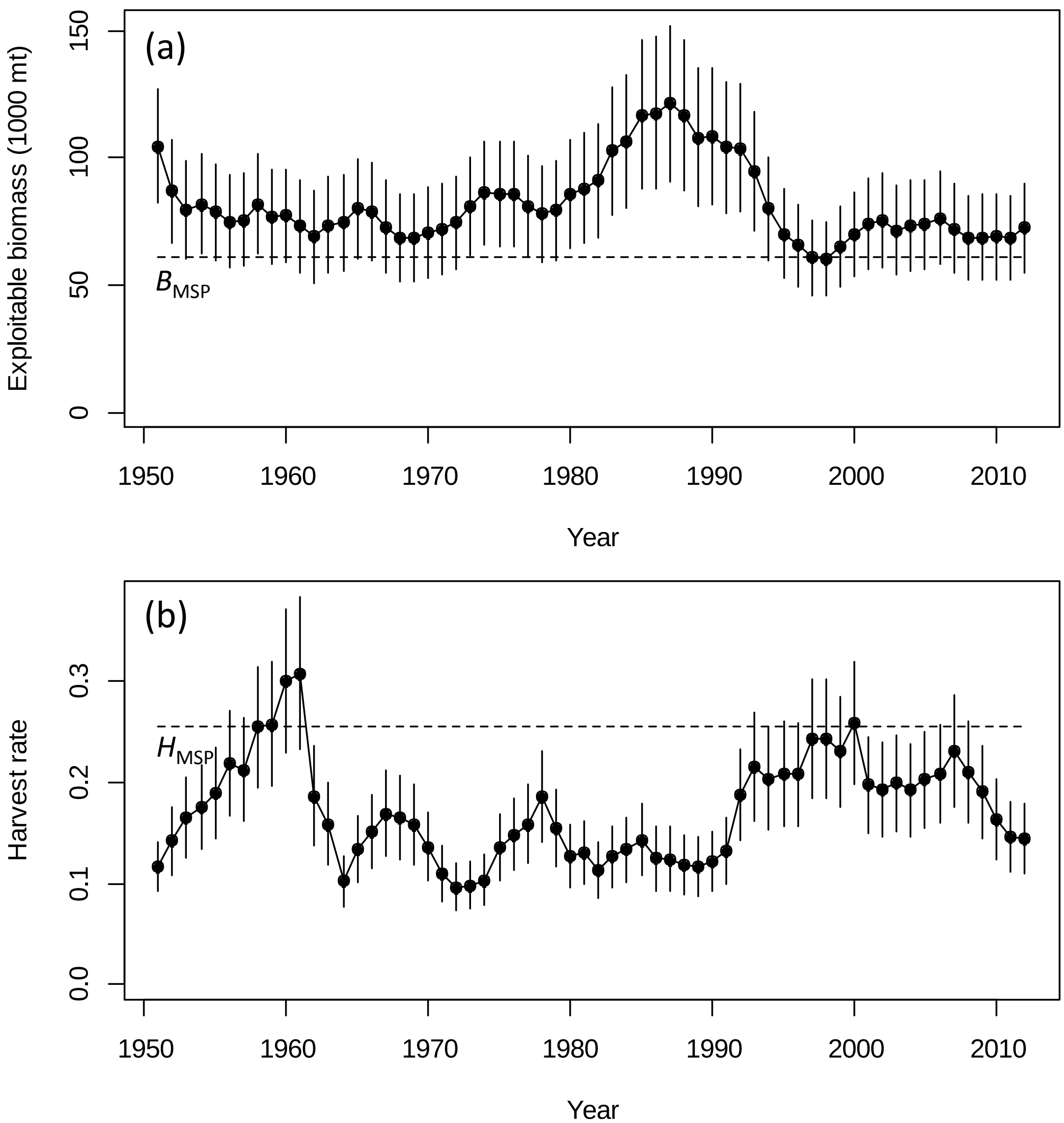

Figure 7. Trends in exploitable biomass (1000 metric ton) (a) and harvest rate (b) of the Western and Central North Pacific swordfish. Error bars denote the 95% confidence interval. The horizontal dashed lines denote the B_{MSP} and H_{MSP}.

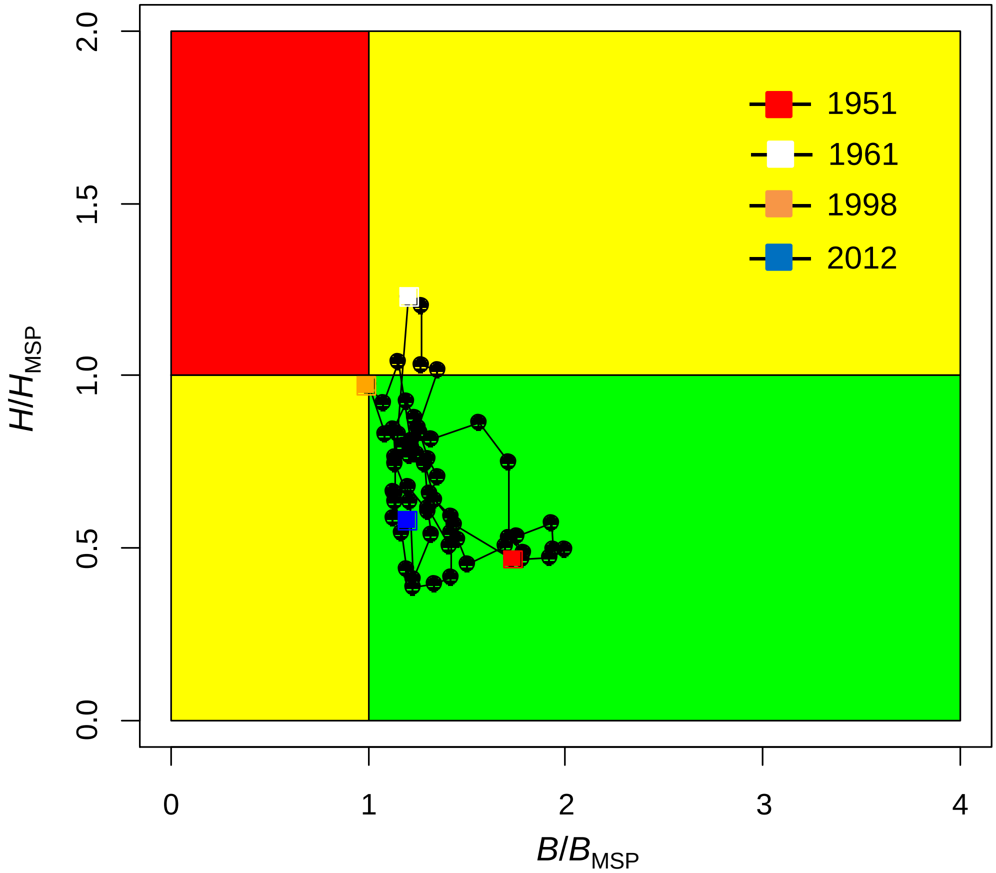

Figure 8. Kobe diagram showing the estimated trajectories (1951-2012) of B/B_{MSP} and H/H_{MSP} for the base-case production model.

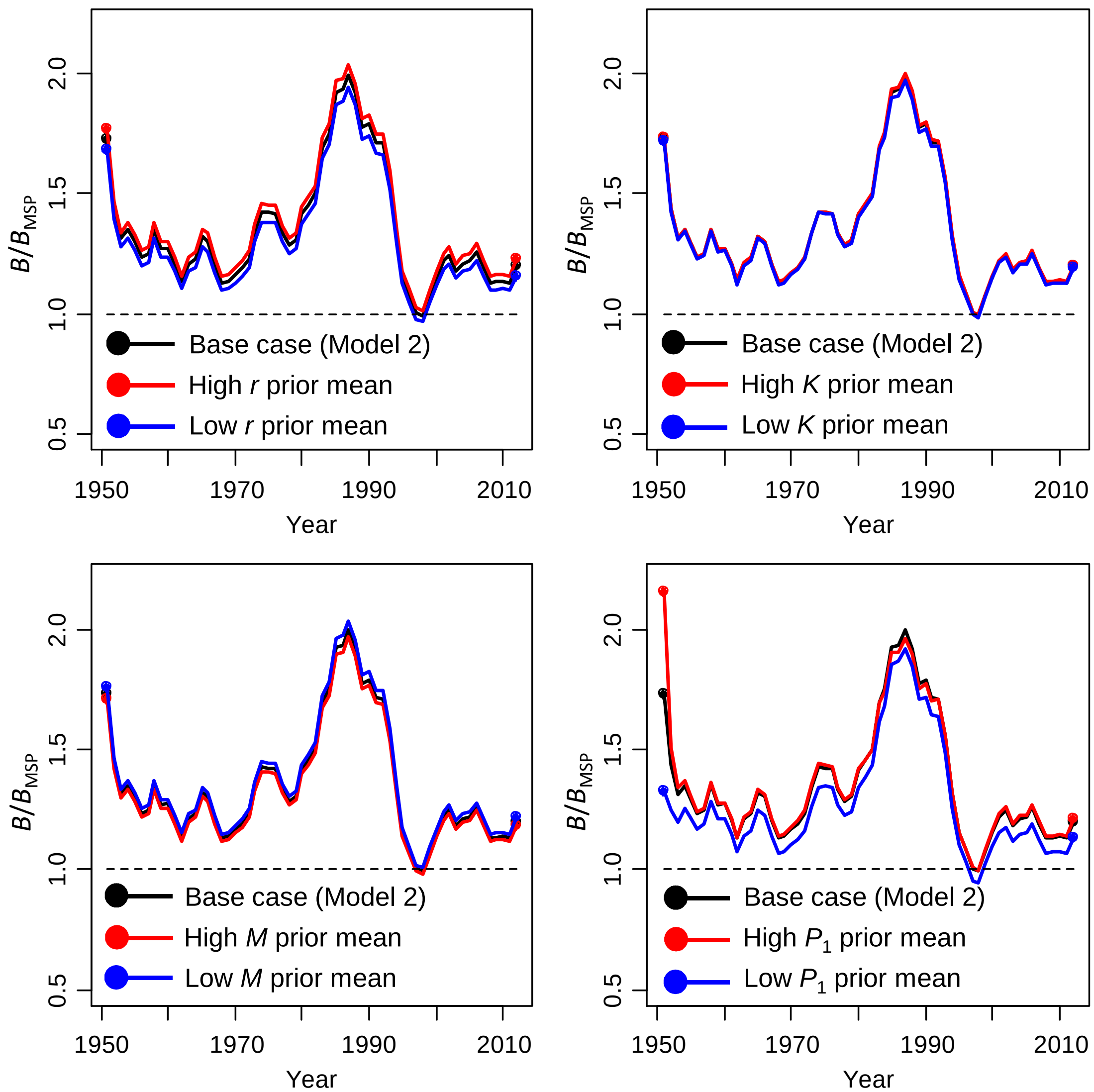

Figure 9. Time-series of ratios of exploitable biomass estimates and maximum surplus production (*MSP*) for the base-case and alternative production models with different prior assumption.

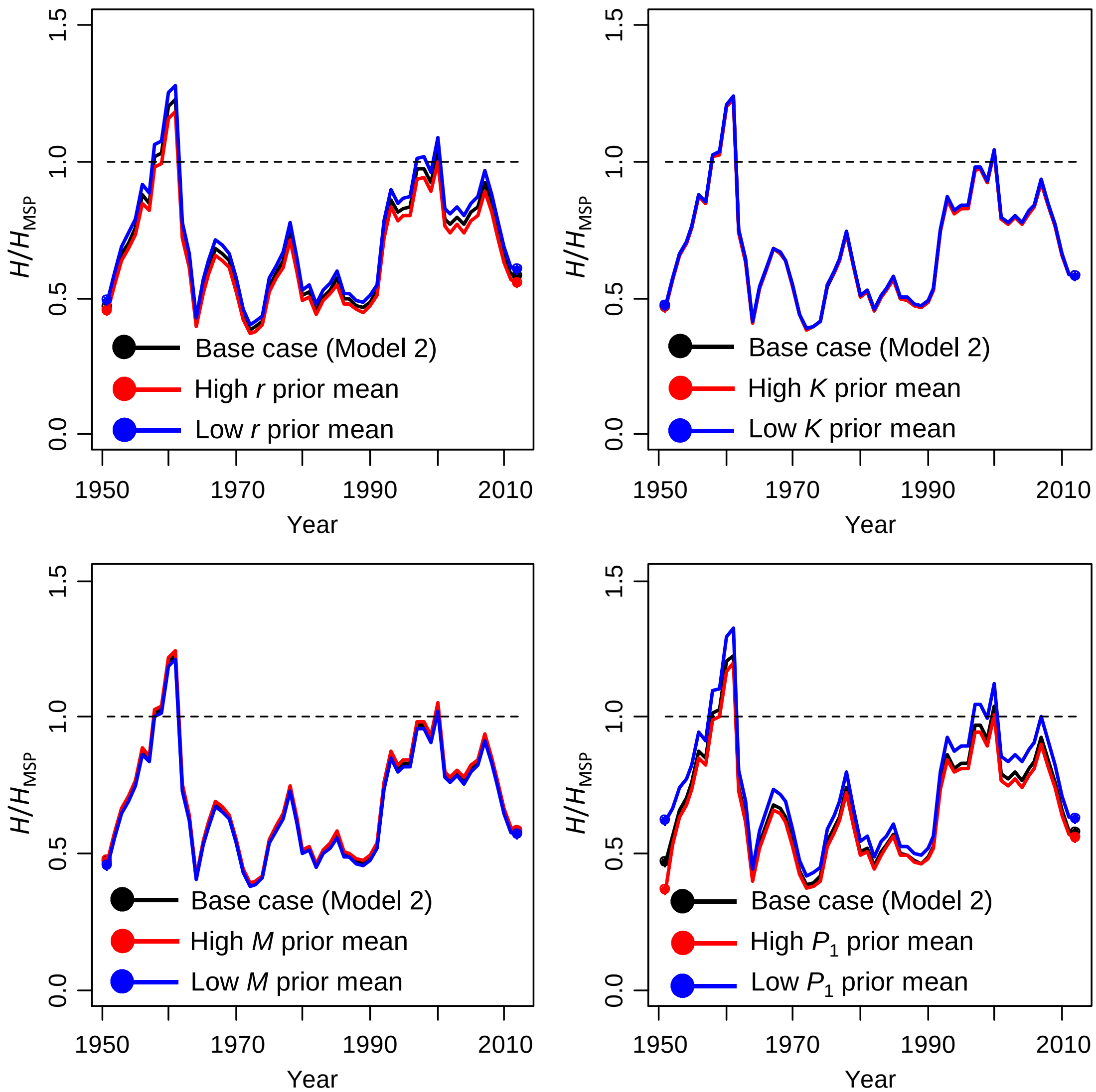

Figure 10. Time-series of ratios of harvest rates and the harvest rate for B_{MSP} (H_{MSP}) for the base-case and alternative production models with different prior assumption.

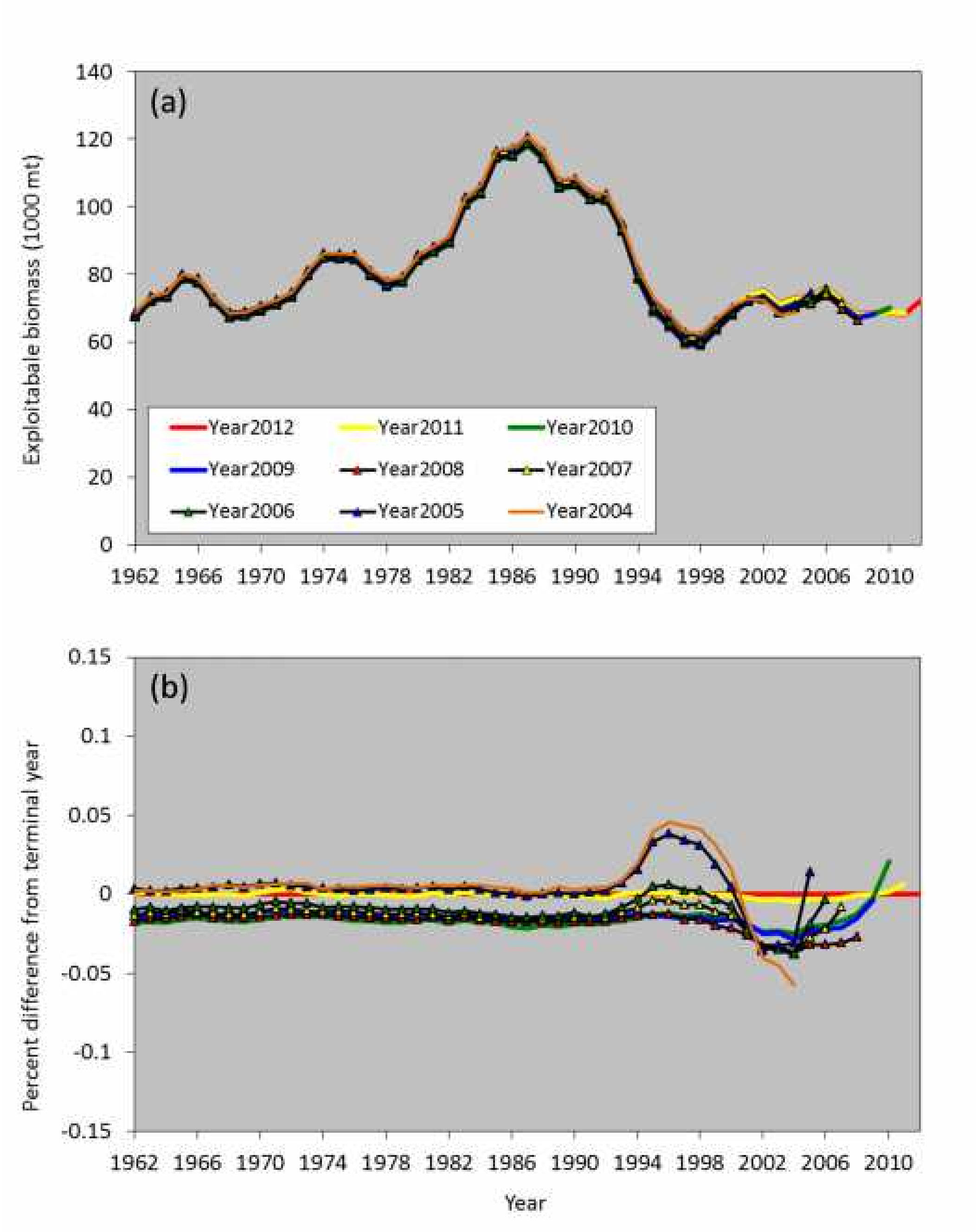

Figure 11. Eight years within–model retrospective plots of the absolute change in biomass (a) and percent difference from terminal year (b) for the Western and Central North Pacific swordfish based on the base-case production model.

Appendix A. Description of Bayesian production model

Annual biomass dynamics:

$$B_t = B_{t-1} + rB_{t-1}\left(1-\left(\frac{B_{t-1}}{K}\right)^M\right) - C_t$$

where B_{t-1} and C_{t-1} denote biomass and catch (landings), respectively, for year t-1. Carrying capacity, K, is the biomass of the population at equilibrium prior to commencement of the fishery; r is the intrinsic population growth rate; and M is the production shape parameter.

We assumed lognormal error structures and used a reparametrization ($P_t = B_t/K$) by expressing the annual biomass as a proportion of carrying capacity as in Millar and Meyer (1999). The state equations are rewritten as

$$P_t = \left(P_{t-1} + r_{t-1}\cdot P_{t-1}\left(1-P_{t-1}^M\right) - \frac{C_{t-1}}{K}\right)\exp(u_t)$$

$$P_1 = \exp(u_1)$$

$$u_1 \sim N\left(«_{P_1}, ±^2_{P_1}\right)$$

$$u_t \sim N(0, ±^2) \quad t = 2,\ldots,N$$

where t is year t, N is number of years, u_1 is a normal random variable with a mean of $«_{P_1}$ and variance $±^2_{P_1}$ to account accounting for the uncertainty of initial condition. u_t is also a normal random variable with a mean of zero and variance σ^2 to account accounting for stochastic process dynamics.

The observation equations are

$$I_{i,t} = q_i K P_t \exp\left(£_{i,t}\right)$$

$$£_{i,t} \sim N\left(0, ²_i^2\right) \quad i = 1 \text{ to } 3;\ t = 1,\ldots,N$$

where $I_{i,t}$ is the relative abundance of index i at time t; q_i is the catchability coefficient for index i, which describes the effectiveness of each unit of fishing effort; and $\varepsilon_{i,t}$ is a normal random variable with a mean of zero and variance $²_i^2$ to account accounting for the natural sampling variation of index i.

Appendix B. Tables and Figures of Base-case Model Results

Table B1. Heidelberger and Welch's (1983) stationarity and half-width tests for the main model parameter in the base-case model.

Node	Stationarity test			Halfwidth test		
	Start iteration	*P*-value	Passed?	Mean	Halfwidth	Passed?
r	4801	0.295	Y	0.575	0.004	Y
K	1	0.562	Y	124.000	0.802	Y
M	9601	0.108	Y	0.985	0.009	Y
P1	1	0.627	Y	0.848	0.001	Y
q_{JPN}	1	0.619	Y	0.003	0.000	Y
q_{TWN}	1	0.482	Y	0.003	0.000	Y
q_{HW}	1	0.829	Y	0.168	0.001	Y
σ^2	1	0.105	Y	0.017	0.000	Y
2^{2}_{JPN}	1	0.476	Y	0.035	0.000	Y
2^{2}_{TWN}	1	0.433	Y	0.095	0.001	Y
2^{2}_{HW}	1	0.623	Y	0.093	0.000	Y

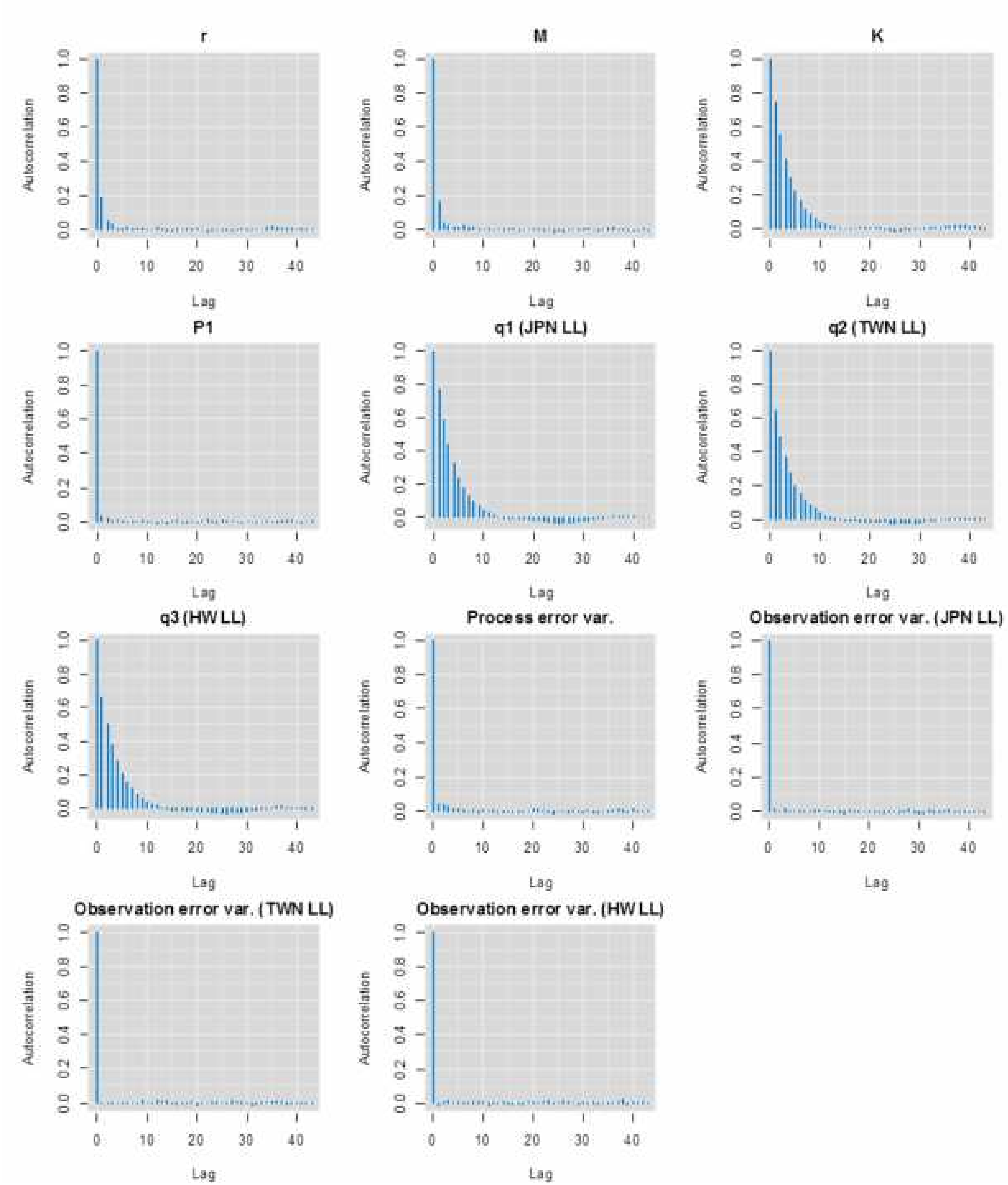

Figure B1. Autocorrelation function plots of main model parameters for the base-case model. Three chains showed highly coherent autocorrelation plots, therefore only chain one was shown in here.

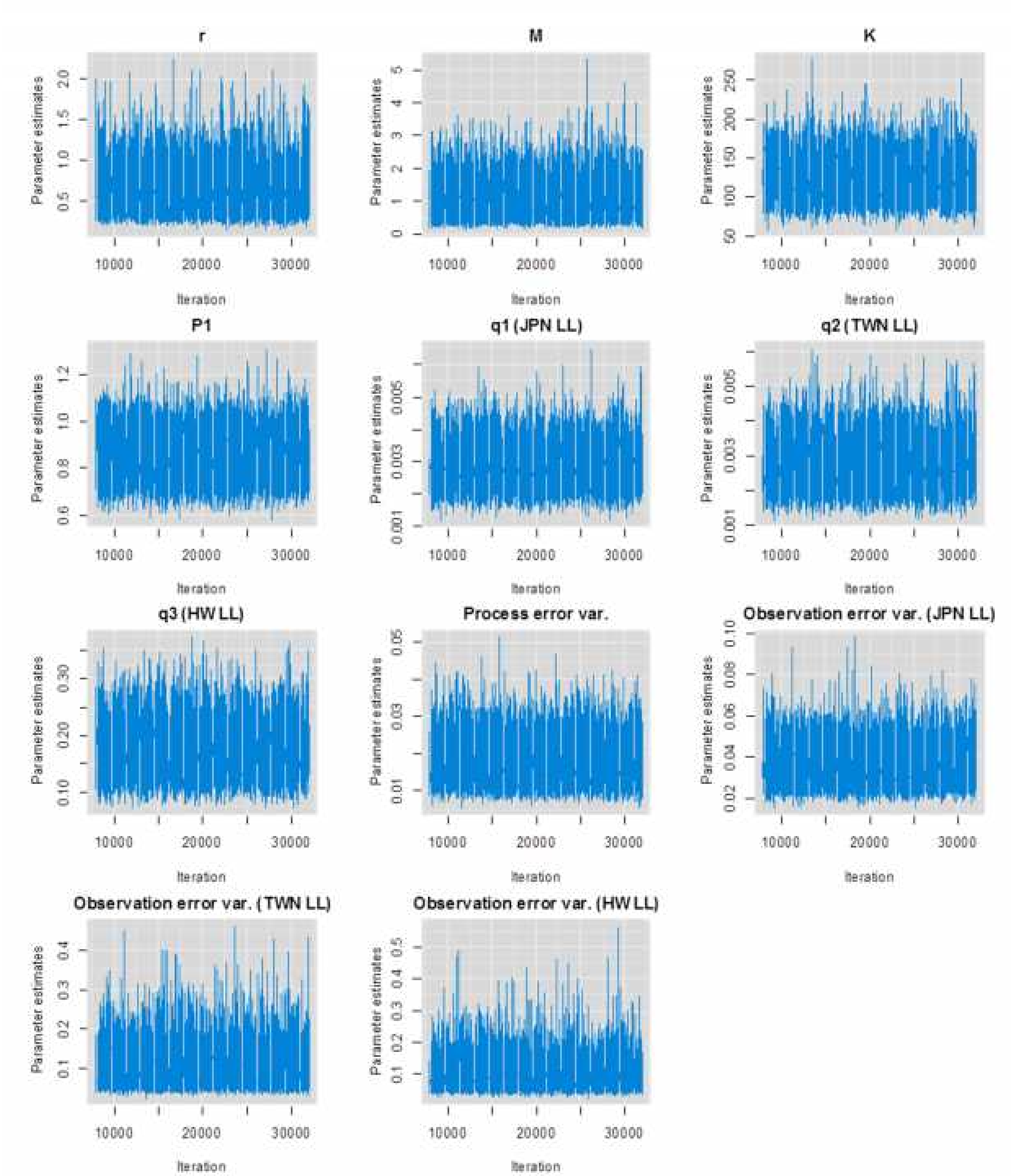

Figure B2. Trace plots for the main model parameter drawn from 24,000 MCMC samples in the base-case model for the WCNPO swordfish. Three chains showed highly coherent trace plots, therefore only chain one was shown in here.

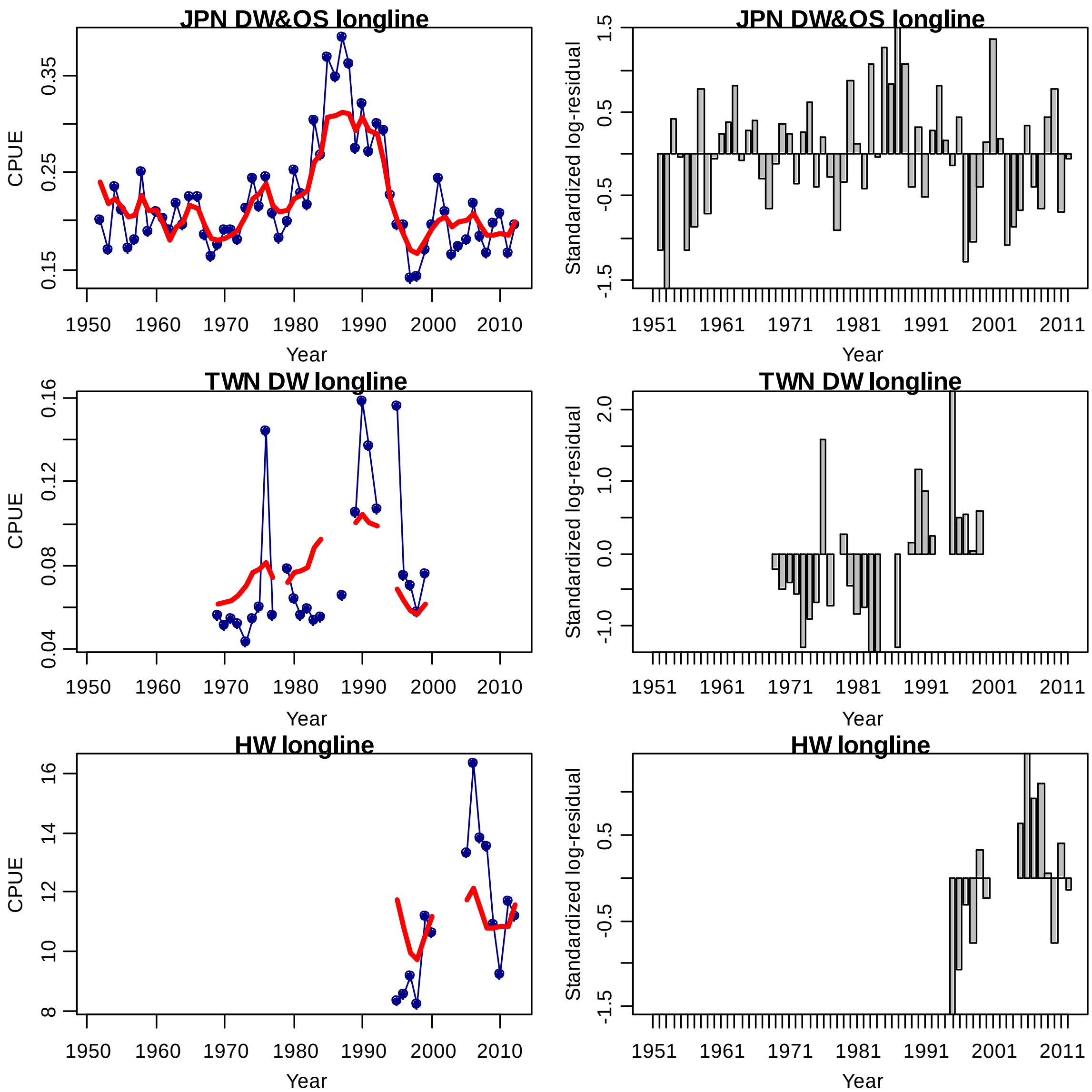

Figure B3.1 Time-series of observed (blue circle line) and predicted (red solid line) catch per unit effort (CPUE) of WCNPO swordfish (left panels) and standardized log-residuals (right panels) for model 1 which included updated catch and all CPUE indices. “JPN” = Japan, “TW” = Taiwan, “HW” = Hawaii, “DW” = Distant water, and “OS” = Offshore.

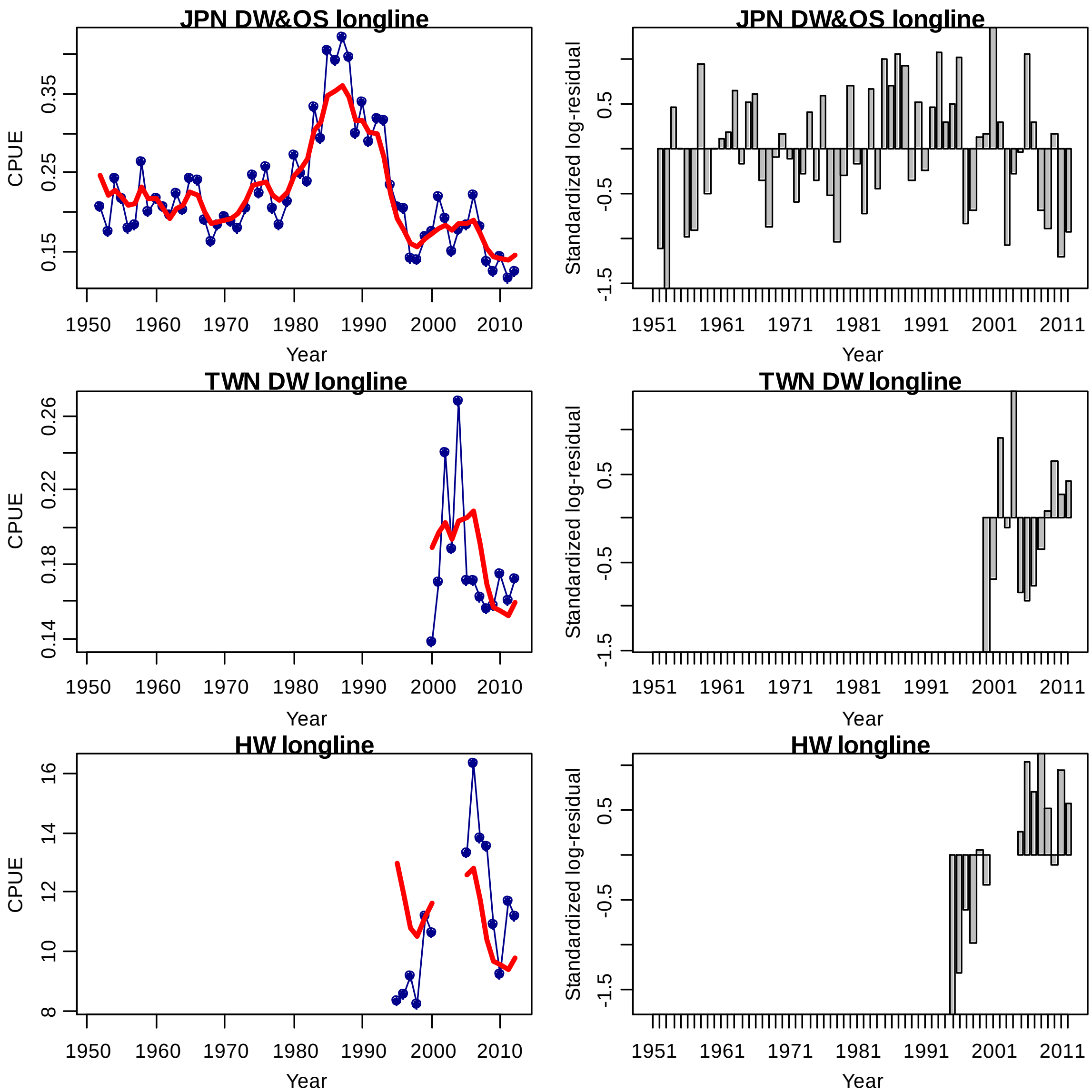

Figure B3.2 Time-series of observed (blue circle line) and predicted (red solid line) catch per unit effort (CPUE) of WCNPO swordfish (left panels) and standardized log-residuals (right panels) for model 3 which used the Japanese longline CPUE without the inclusion of catch-effort data in the areas along the border of the WCNPO and EPO swordfish stocks. “JPN” = Japan, “TW” = Taiwan, “HW” = Hawaii, “DW” = Distant water, and “OS” = Offshore.

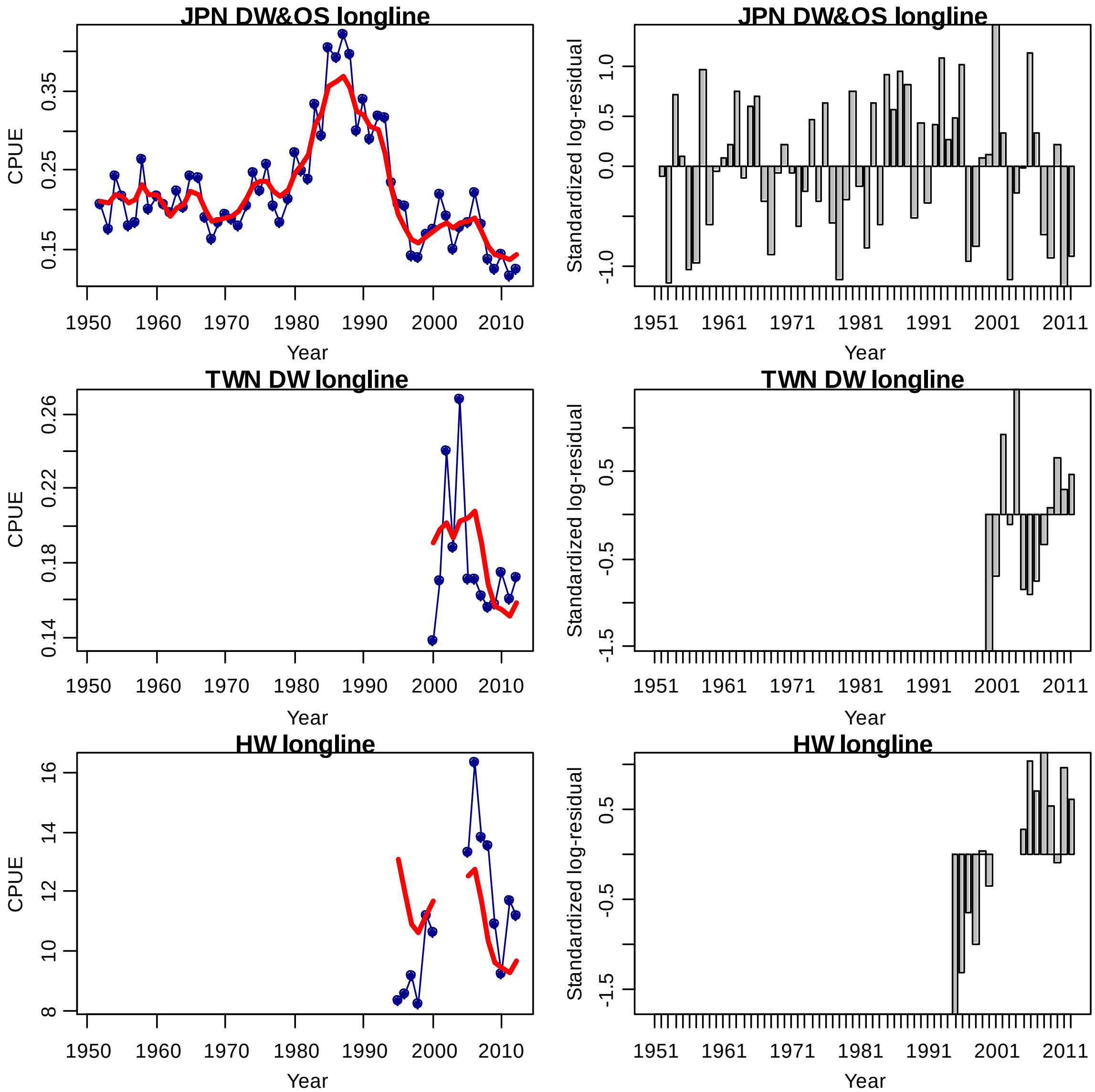

Figure B3.3 Time-series of observed (blue circle line) and predicted (red solid line) catch per unit effort (CPUE) of WCNPO swordfish (left panels) and standardized log-residuals (right panels) for model 4 which used a CV of 50% for the lognormal prior distribution of the proportion of initial carrying capacity. “JPN” = Japan, “TW” = Taiwan, “HW” = Hawaii, “DW” = Distant water, and “OS” = Offshore.