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Stock Assessment for the North Pacific Blue Shark (*Prionace glauca*) Using a Bayesian State-Space Surplus Production Model[1]

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Abstract

Stock assessment for North Pacific blue shark were conducted using newly available data, parameters and model. The span was extended from 1971-2011 to 1971-2015. New abundance indices of Mexico longline during 2006 and 2015 was added to the five abundance indices used for the previous stock assessment in 2014. The stock assessment model "BSSPM" was used instead of "BSP2". New diagnostics such as WAIC and SDNR were used, and future projection was conducted with four harvest scenarios for 10 years. Since Japanese offshore shallow-set longline (**JPE** and **JPL**) is the most representative abundance indices due to the large area coverage, the large amount of data, and the longest time series, the stock status of North Pacific blue shark was exhibited using a reference case based on the Japanese longline data. Our results (**JPE-JPL**) indicated that the median estimates of stock biomass fluctuated around 630,000 tons in 1970s, and then declined to the lowest level of 343,915 tons in 1989, thereafter increased to 688,429 tons in 2003, and fluctuated around 560,000 tons in recent years. Estimated harvest rate sharply increased from the early 1970s to the 1980s, peaked at 0.184 $year^{-1}$ in 1989, in response to the high catch in 1970s, thereafter sharply declined in 1990s and to 0.067 $year^{-1}$ in the most recent years (2012-2014). Given the MSY is used as default reference points because management has not set reference points, the current stock biomass (B) (2012-2014) was 20% above B_{MSY} and the current harvest rate(H) (2012-2014) was 48% below H_{MSY}. The results of the base-parameter model based on the Japanese longline fishery suggested that the North Pacific blue shark stock was not overfished and was not subject to overfishing relative to the MSY-based reference points. Future projections suggested that a scenario with H_{MSY} allowed to increase the catch above the MSY level. Inconsistent trends between decrease of total catch and decrease of abundance indices for Mexico longline indicated a local depletion of the stock biomass in the eastern Pacific Ocean.

1. Introduction

Blue shark (*Prionace glauca*) is a top predator and highly migratory pelagic shark found throughout the world in tropical and temperate seas (Nakano and Stevens, 2008). It is the most abundant pelagic shark species in the world (Nakano and Seki, 2003). The stock structure of blue shark in the Pacific comprises two stocks based on biological and fishery evidence as well as a genetic study (ISC, 2014; King *et al*., 2015). One stock is in the North pacific and the other is in the South Pacific.

A stock assessment of North Pacific blue shark was conducted in 2014 (ISC, 2014) using a state-space Bayesian surplus production model (BSP2) that the software was developed for ICCAT (McAllister and Babcock, 2006). In the stock assessment, five CPUEs (Japanese offshore shallow-set longline from 1976 to 1993, Hawaii deep-set longline from 2000 to 2011, Japanese offshore shallow-set longline from 1994 to 2010, SPC observed longline from 1993 to 2009, Taiwan large-scale longline from 2004 to 2011) and a combined catch data from 1971 to 2011 were used to account for a full range of uncertainties associated with stock dynamics. The assessment results were different among CPUEs with respect to median estimates, however, similar stock status and future projections were generally produced. The stock biomass in 2011 was well above the biomass at maximum sustainable yield (B_{MSY}), and the fishing mortality rate in 2011 was well below F_{MSY}. However, some uncertainties about stock status were recognized in some reference cases and the related sensitivity runs. These uncertainties were associated with catch data estimates, biological and demographic parameters, and model structures.

This working paper provides the stock assessment results of North Pacific blue shark using a Bayesian State-space Surplus Production Model (BSSPM) that the software was developed by Carvalho and Brodziak (2016) with update of the fishery data as well as the biological parameters.

2. Materials and Methods

2.1. Catch data

We used a total amount (total dead removals) of blue shark's catch (tons) caught in the North Pacific during 1971 and 2015 (**Table 1**, **Figure 1**) that collected from seven countries (Canada, China, Japan, Mexico, South Korea, Taiwan, USA), one tuna-RFMO (IATTC) and non ISC member countries (SPC). The total amount of catch sharply increased in 1970s and reached to the highest level (87,000 tons) in 1981, and then it had decreased until 2015 with a slight fluctuation (**Figure 1**). The current total catch in 2015 was 32,956 tons (**Table 1**). Japanese and Taiwanese catches accounted for a high proportion of catches (73-99%) throughout the years.

2.2. CPUE data

We used single standardized CPUE (Japanese offshore shallow-set longline: **JPE**) of blue shark during 1976 and 1993, and five standardized CPUE (Japanese offshore shallow-set longline: **JPL**, Hawaii deep-set longline: **HWI**, Mexico longline: **MEX**, SPC observed longline: **SPC**, Taiwan large-scale longline: **TWN**) of blue shark during 1994 and 2015 but the length of each time series was different by fleet (**Table 2**, **Figure 2**). The relative CPUE to its mean were assumed to have log-normally distributed errors with standard error (SE) expressed in log-space (log(SE)) as $(\log(1+CV^2))^{1/2}$, where CV is coefficient variation. The log (SE) of each CPUE were estimated by the statistical model in the standardization process (See document paper of the CPUE standardization for each fleets). The estimated log (SE) only captures observation error within the statistical model but it does not reflect the inherent process error between the unobserved vulnerable population and the observed CPUE. We therefore assumed a minimum average log (SE) for each CPUE of 0.1. If the average log (SE) for each CPUE was smaller than 0.1, the estimated log (SE) was scaled to 0.1. If the average estimated log (SE) was larger than 0.1, the estimated mean values

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were remained as it were.

Standardized CPUE of **JPE** showed a decreasing trend from 1976 to 1990 and then sharply increased until 1993 (**Figure 2**). Standardized CPUE of **JPL** exhibited an increasing trend until 2003 and then historically kept stable around the average level (**Figure 2**). Standardized CPUE of **MEX** showed a large fluctuation and a decreasing trend. Standardized CPUE of **SPC** sharply increased from 1995 to 1998 and then sharply declined until 2009. Standardized CPUE of **TWN** also showed a large fluctuation and an increasing trend in recent several years. Standardized CPUE of HWI illustrated a sharp decreasing trend until 2008 and then sharply increased.

2.3. Model description

We used the BSSPM (Carvalho et al., 2016) instead of BSP2 (McAllister and Babcock, 2006) because the BSSPM produced similar stock assessment results in 2014 if the same data and prior distributions for key parameters were used (Carvalho et al., 2016). In addition, the BSSPM provides direct estimates of parameter uncertainty that are straightforward to interpret, and Bayesian posterior distributions for quantities of management interest using the Markov Chain Monte Carlo (MCMC) algorithm were developed (Carvalho et al., 2016). However, the careful consideration about co-relation among parameters is required in the evaluation of the model because it is the main reason that BSP2 was used in the former stock assessment (see section about the convergence criteria for the posterior distribution).

2.3.1 Surplus Production Model (SPM)

First, we focus on the surplus production function of the generalized three parameter Surplus Production Model (Pella and Tomlinson, 1969):

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

where t is the year, B is the biomass, r is the intrinsic rate of population biomass, K is the unfished biomass, C is the catch, and m is the shape parameter ($m > 1$) that determines at which B/K ratio maximum surplus production is attained. If the shape parameter (m) is 2, the model reduces to the Schafer form, with the surplus production attaining the maximum sustainable yield (MSY) at exactly $K/2$. If the shape parameter satisfies with $1 < m < 2$, surplus production attains MSY at depletion levels smaller than $K/2$. If the shape parameter is larger than 2, surplus production attains MSY at higher levels larger than $K/2$. Given that $m \approx 1$, the Pella and Tomlinson model reduces to the Fox model that results in MSY at approximately 0.368 K, however, there is no exact solution if $m = 1$. Under that the catch C is defined as the product of H and B, where H is the harvest rate, with the equilibrium status ($B_{t+1} = B_t$), the Equation (1) gives biomass at MSY (B_{MSY}):

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$$B_{\mathrm{MSY}} = K m^{\frac{-1}{m-1}}. \tag{2}$$

The corresponding harvest rate at MSY (H_{MSY}) is

$$H_{\mathrm{MSY}} = \frac{r}{m}. \tag{3}$$

Therefore, m can be directly translated into B_{MSY}/K from the Equation (2) and thus determines the biomass depletion level where MSY is achieved (Thorson *et al*., 2012).

2.3.2 Bayesian State-Space formulation

We formulated the BSSPM building on the Bayesian state-space estimation framework (Meyer and Millar, 1999; Brodziak and Ishimura 2011). The biomass B_t was expressed as proportion of K (i.e. $P_t = B_t/K$) to improve the efficiency of the estimation algorithm. The model was formulated to accommodate multiple CPUE for fisheries f. The initial biomass in the first year (t=0) of the time series was scaled by introducing model parameter φ to estimate the ratio of the biomass in the first year (B_{1971}) to unfished biomass (K) (i.e. $\varphi = B_{1971}/K$). The stochastic form of the process equation was given by:

$$\begin{aligned} P_t &= \varphi \exp(\eta_t), && \text{if } t = 1 \\ P_{t+1} &= \left\{P_t + \frac{r}{m-1} P_t\left(1 - {P_t}^{m-1}\right) - \frac{\sum_f C_{f,t}}{K}\right\} \exp(\eta_t), && \text{if } 2 \le t \le n \end{aligned} \tag{4}$$

where η_t is the process error, with $\eta_t \sim N(0, \sigma_\eta^2)$ where σ_η^2 is the variance of the process error, and n is the terminal year which is equivalent to the total number of the years. The observation equation was given by:

$$U_{f,t} = q_f K P_{f,t} \exp(\varepsilon_{f,t}) \qquad t = 1, 2, \dots, n. \tag{5}$$

where q_f is the estimable catchability coefficient associated with the abundance index U for fishery f and $\varepsilon_{f,t}$ is the observation error, with $\varepsilon_{f,t} \sim N(0, \sigma_{\varepsilon,f,t}^2)$ where $\sigma_{\varepsilon,f,t}^2$ is the variance of the observation error.

The full BSSPM projected over n years requires a joint probability distribution over all unobservable hyper-parameters $\boldsymbol{\theta} = \{K, r, \varphi, \sigma_\eta^2, q_f, \sigma_{\varepsilon,f,t}^2\}$ and the n process errors relating to the vector of unobserved states $\boldsymbol{\eta} = \{\eta_1, \eta_2, \dots, \eta_n\}$, together with all observable data in the form of the relative abundance indices for fisheries f, $\mathbf{U}_f = \{U_{f,1}, U_{f,2}, \dots, U_{f,n}\}$(Meyer and Millar, 1999). Based upon the Bayes' theorem, it follows that joint posterior distribution over all unobservable parameters, given the data and unknown states, can be formulated as:

$$\begin{aligned} p(\boldsymbol{\theta}|\boldsymbol{\eta}, \mathbf{U}) = {} & p(K)p(r)p(\varphi)p(\sigma_\eta^2)p(q_f)p(\sigma_{\varepsilon,f,t}^2) \times p(P_1|\varphi, \sigma_\eta^2) \\ & \times \prod_{t=2}^{n} p(P_{t+1}|P_t, K, r, \sigma_\eta^2) \times \prod_{t=1}^{n} p(U_{f,t}|P_{f,t}, q_f, \sigma_{\varepsilon,f,t}^2). \end{aligned} \tag{6}$$

2.3.3 Prior formulation

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Priors for the reference case scenarios were formulated as those used in the BSP2 (ISC, 2014) and comprised of uniform prior distributions for log (K) and q and lognormal distributions for r and $\varphi = B_{1971}/K$ (see Table 2 in ISC, 2014). The prior means for r were translated into H_{MSY} using Equation (3) and fixed input values for the shape parameter m were obtained through iterative search as a function of B_{MSY}/K using Equation (2).

2.3.4 Convergence to posterior distribution

A critical issue in using MCMC methods is how to determine if random draws have converged to the posterior distribution. Convergence of the MCMC samples to the posterior distribution was checked by monitoring the trace and by diagnosing the autocorrelation plot **(Fig. A1)**. Potential scale reduction factor (Rhat) and statistical test (Geweke) were also implemented (**Table A1**). In this study, three MCMC chains were used. The model was run for one million iterations, sampled with a thinning rate of 200 with a burn-in period of 0.2 million for three chains.

2.4. Specification and parameterization

The parameters used for the reference and sensitivity runs were summarized in **Table 3**. We named the model consisted of the default parameters "**base-parameter model**". The range of the uniform distribution for the prior means of unfished biomass (K) was arbitrarily chosen between 100,000 and 20,000,000 tons. The prior means of intrinsic rate of population biomass (r) for reference case was estimated from two-sex matrix population dynamics model (Yokoi *et al*., 2016) with the updated growth and reproductive parameters (Fujinami *et al*., 2016; Fujinami *et al.* In press) and new natural mortality schedules (M-schedules) from Walter *et al*. (2016) method-II (Semba and Yokoi, 2016). Higher alternative prior mean was used from Cortés (2002) and Kleiber *et al*. (2009) as in ISC (2014), whereas lower alternative prior mean was estimated using the similar methods for reference case except with 2-year breeding periodicity instead of 1-year breeding periodicity. The standard deviation (SD) of r for reference case and alternative runs was arbitrarily given.

The prior of the ratio ($\varphi = B_{1971}/K$) for reference case was given by expert opinion after considering the several studies on the initial population size in addition to the report with regards to longline effort in the North Pacific since 1950 (Okamoto, 2004; Ohshimo *et al*., 2014; Ward and Myers, 2005). Higher and lower prior means for the ratio (φ) were arbitrarily given. The SD of φ for reference case and alternative runs was arbitrarily given as well.

The shape parameter (m) for reference case was calculated using the empirical equation (Fowler, 1988):

$$m = 0.633 - 0.187 \times \ln(rT), \qquad (7)$$

where r =0.221 was given with the updated biological parameters and the generation time (T) was assumed to be 7 based on Cortés (2002) as in the 2014 assessment. In the calculation of the shape

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parameter (m) with use of equation (7), the value of the generation time is required. The generation time is estimated using the following equation:

$$\mathrm{T} = \sum_{x=0}^{max} x l_x b_x e^{-rx} \tag{13}$$

where x is age, l is survival rate, and max is maximum age. Two sex matrix population model (Yokoi et al., 2016) can provide the generation time however it is required to correct the above equation due to two-sex model (the generation time is generally estimated using only female's parameter). It is therefore generation time was assumed to be 7.0 based on Cortes (2002). Higher and lower values of shape parameter (m) were calculated using r = 0.187 and 0.34 with T = 7, respectively. The former value of r was estimated using updated biological parameters with 2-year breeding periodicity and latter value was estimated using biological parameters as in the 2014 assessment. The shape parameter was estimated in the model as an alternative run.

Process error ($\eta = 0.07$) was arbitrarily given and an attempt was made to estimate it in the model as an alternative run for the reference case.

The different combinations of r vs φ and r vs m were used to examine the sensitivity of the key parameters to the output. The impact of the different productivity (r) from the different M-schedules on the output was also examined (**Table A2**). A total number of 25 sensitivity runs were conducted for each reference case of the **base-parameter model**.

2.5. Diagnostics

2.5.1. Retrospective analysis

Retrospective analysis is widely used in stock assessments to evaluate the reliability of parameter and reference point estimates (Cadigan and Farrell, 2005; Hurtado-Ferro *et al*., 2014). Retrospective analysis involves fitting a stock assessment model to the full dataset, and the same model is then fitted to truncated datasets where the data for the most recent years have been sequentially eliminating one year of data each time (model runs with fewer data are referred to as "peels"). Finally, 10 years' data points were removed from the estimates (i.e. 2006-2015). Mohn's "ρ" was calculated for stock biomass and harvest rate using the formulation proposed by Hurtado-Ferro *et al*. (2014).

$$\rho = \overline{\left(\frac{X_{Y-y,p} - X_{Y-y,\mathrm{ref}}}{X_{Y-y,\mathrm{ref}}}\right)} \tag{8}$$

where X is the quantity (i.e. Relative B/B_{MSY} to B_{1971}/B_{MSY} and Relative H/H_{MSY} to H_{1971}/H_{MSY}) for which Mohn's ρ is being calculated, Y is the final year of the stock assessment, i.e. 2015, y is the last year of a given "peel" p (2014, 2013, … ,2005), and ref the reference peel, i.e. the most recent assessment.

2.5.2. Residual analysis

For each CPUE, the standard deviation of the normalized (or standardized) residuals (SDNR) was

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used to examine the goodness-of-fit to CPUE data (Francis, 2011). To calculate the SDNR for a data set, we first calculate the normalized residual for each data point and then use the usual formula to calculate the standard deviation of these residuals:

$$\mathrm{SDNR} = \sqrt{\frac{\sum_i^n (z-\bar{z})^2}{n}},\ z = \frac{O-E}{\sigma_{O-E}} \tag{9}$$

where z is a normalized residual, O is an observed value, E is an expected value, $\sigma_{O\text{-}E}$ is a standard deviation between O and E. The SDNR should be less than $[\chi^2_{0.95,m-1}/(m-1)]^{0.5}$ to statistically confirm whether the fitting to CPUE data is good, where $\chi^2_{0.95,m-1}$ is the 95$^{\text{th}}$ percentile of a χ^2 distribution with m-1 degrees of freedom (Anon., 2016). We also conducted a visual examination between observed and predicted values because Francis (2011) noted that it is essential to confirm the fitting even when the SDNR are smaller than the benchmark. The results showed that SDNRs for all CPUE indicated the statistically good fit (**Table A3**).

2.5.3. WAIC

Watanabe-Akaike (or widely applicable) information criterion (WAIC) is an information criterion based on Bayesian statistics (Watanabe, 2010; Gelman et al., 2013). WAIC is commonly used for model selection by predictability of model. Given N number of data (x) for a variable X ($X^N = (x_1, x_2, \cdots, x_N)$) and parameters ($\boldsymbol{\theta}$),the WAIC is defined as follows:

$$WAIC = -\frac{1}{N}\sum_{i=1}^{N} log\mathbb{E}_{\boldsymbol{\theta}}[p(x_i|\boldsymbol{\theta})] + \frac{1}{N}\sum_{i=1}^{N}\{\mathbb{E}_{\boldsymbol{\theta}}[(\log p(x_i|\boldsymbol{\theta}))^2] - \mathbb{E}_{\boldsymbol{\theta}}[\log p(x_i|\boldsymbol{\theta})]^2\} \tag{10}$$

where p is a probability distribution and $\mathbb{E}_{\boldsymbol{\theta}}[\cdot]$ is the expected value from the posterior distributions:

$$\mathbb{E}_{\boldsymbol{\theta}}[\cdot] = \int [\cdot]\, p(\boldsymbol{\theta}|X^N)\, d\boldsymbol{\theta}. \tag{11}$$

The concept of the Eq. (10) is that the first term means the expected mean value from the likelihood and posterior distribution and the second term means the variances. Given the posterior distribution can be approximated by a normal distribution, WAIC and AIC are asymptotically equivalent. Smaller value of WAIC indicates that the average error of the predicted values from the true model be smaller. We named the selected model by WAIC "**best-parameter model**".

2.5.4. Prior-only run

We ran a **base-parameter model** without fitting to the CPUEs (i.e. prior-only run) to examine the relative influence of priors and data on the marginal posterior distributions (i.e. median and CV) for key parameters. This was denoted as the prior only model.

2.6. Forecast

We conducted a future projection from 2015 to 2024 using software developed to evaluate the impact of various levels of fishing intensity on future biomass and catch. The model structure is the same as that used in the stock assessment:

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$$B_{t+1} = B_t + \frac{r}{m-1} B_t \left(1 - \left(\frac{B_t}{K}\right)^{m-1}\right) - B_t H_t \tag{12}$$

and the median and the 95 % credible intervals of the forecasted time series were estimated using BSSPM. In the forecast, relative harvest rate (*H*) to the average value in the three years from 2012 to 2014 was used under four different harvest scenarios.

(1) High *H* scenario indicates that the relative harvest rate increases by 20%.

(2) H_{MSY} scenario indicates that the relative harvest rate sustains at MSY level.

(3) Status-Quo *H* scenario indicates that the relative harvest rate maintains at an average value in the three years from 2012 to 2014.

(4) Low *H* scenario indicates that the relative harvest rate decreases by 20%.

Note that we used the harvest rate (*H*) instead of fishing mortality rate (*F*) due to the structure of the model.

3. Results

As the result of the model selection by WAIC in **Table 4**, different model was selected from the sensitivity runs as the best model for each reference case. The shapes of the posterior distributions for key parameters and variables were apparently different between the **base-parameter model** and the **best-parameter model** (**Table 5**, **Fig, 3**). However, the values of WAIC between them were almost same except four reference cases (**JPE-TWN**, **MEX**, **SPC** and **TWN**). In addition, yearly changes in the relative values to the reference points (B/B_{MSY} and H/H_{MSY}) were almost similar between them (**Table 5**, **Fig. 4**). Therefore, we only show the results of the **base-parameter model** hereafter. Additionally, we focused on the results of five reference cases (**JPE-JPL**, **JPE-HWI**, **JPE-MEX**, **JPE-SPC**, **JPE-TWN**) that used Japanese CPUE data before 1994. The results of the remaining five reference cases (**JPL**, **HWI**, **MEX**, **SPC**, **TWN**) were shown in the **Appendix (Figs. A2-A7)**.

Annual changes in the biomass (*B*) and harvest rate (*H*) during 1971 and 1993 for five reference cases, except for *B* of **JPE-TWN**, showed that the *B* was above $B_{\mathbf{MSY}}$ and *H* was below $H_{\mathbf{MSY}}$ in 1970s, and the tendency was vice versa in 1980s (**Figs. 5**, **6**). The trends in *B* and *H* after 1990 were strongly dependent on those in CPUEs. **JPE-JPL** showed that *B* was above B_{MSY} from the mids-1990s until 2015 and *H* was below $H_{\mathbf{MSY}}$ since 1990. Both **JPE-HWI** and **JPE-SPC** showed that *B* and *H* were slightly fluctuated around the MSY level. **JPE-MEX** exhibited that *B* was below B_{MSY} and *H* was above $H_{\mathbf{MSY}}$ from 1990 to 2015. **JPE-TWN** showed that *B* was below B_{MSY} throughout the stock assessment period and *B* was increased in recent years, and *H* was below H_{MSY} after 1990.

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Kobe-plot showed that the current stock status for five reference cases were divided into three: green zone (**JPE-JPL**, **JPE-TWN**), yellow zone (**JPE-HWI**, **JPE-SPC**), and red zone (**JPE-MEX**) (**Fig. 7**).

Sensitivity analyses showed that the absolute values (*B* and *H*) were different among 26 runs, however, trends in the relative values (B/B_{MSY} and H/H_{MSY}) were almost same among 26 runs (**Table 6**, **Fig. 8**).

Retrospective analysis showed that there were no significant trends in relative biomass (B/B_{MSY}) and relative harvest rate (H/H_{MSY}) (**Fig. 9**). The low values of Mohn's rho (0.018 for biomass and -0.016 for harvest rate) indicated less biased estimates.

Future projections showed that the catch constantly increased with the increase of the biomass except for **JPE-MEX** and H_{MSY} scenario for some reference cases (**Table 7**, **A4**, **Fig. 10**). In case of H_{MSY} scenario for two reference cases (**JPE-JPL**, **JPE-TWN**), the catch sharply increased with the increase of the harvest rate, while biomass declined to B_{MSY} with the increase of the catch and the decrease of biomass that resulted in the decrease of the catch. For the other reference cases (**JPE-HWI**, **JPE-SPC**), H_{MSY} scenario showed that catch slightly increased due to the slight increase of biomass. In case of H_{MSY} scenario for **JPE-MEX,** biomass gradually approached to B_{MSY}, however, the catch departed from the MSY level due to the low biomass relative to B_{MSY}.

4. Discussion

We updated the stock assessment for North Pacific blue shark using the BSSPM model with newly available abundance indices, catch, and key parameters. We extended the time series from 1971-2011 to 1971-2015. We also added new abundance indices of Mexico longline (**MEX**) in addition to the four abundance indices (**JPL**, **HWI**, **SPC**, and **TWN**) during 1994 and 2015 (**Fig. 2**). In the five abundance indices, Japanese offshore shallow-set longline (**JPL**) is the most representative abundance indices because of the large area coverage, large amount of data, and the longest time series (Hiraoka et al. 2016). Our results (**JPE-JPL**) indicated that the median estimates of stock biomass fluctuated around 630,000 tons in 1970s, and then declined to the lowest level of 343,915 tons in 1989, thereafter increased to 688,429 tons in 2003, and fluctuated around 560,000 tons in recent years (**Fig. 6**). Estimated harvest rate sharply increased from the early 1970s to the 1980s, peaked at 0.184 year^{-1} in 1989, in response to the high catch in 1970s, thereafter sharply declined in 1990s and to 0.067 year^{-1} in the most recent years (2012-2014). Given the MSY is used as reference points, the current stock biomass (*B*) (2012-2014) was 20% above B_{MSY} and the current harvest rate (*H*) (2012-2014) was 48% below H_{MSY}. The results of the **base-parameter model** based on the Japanese longline fishery suggested that the North Pacific blue shark stock was not overfished and was not subject to overfishing relative to the MSY-based reference points.

Unlike the optimistic stock assessment results based on the Japanese abundance indices (**JPE-JPL**), the stock assessment results based on the Mexico abundance indices **(JPE-MEX)** indicated the pessimistic stock status (**Fig. 7**). However, the interpretation of the stock assessment results was difficult because the decreasing trends of recent catch would be increased abundance indices, however, the trends of Mexican CPUE was decreasing. Probably, the inconsistent trend between the total catch and the CPUE is due to a local depletion of the stock in the eastern Pacific Ocean or any other changes in the migration patterns due to the environmental effects. The stock assessment results based on the Taiwanese abundance indices **(JPE-TWN)** which have large area coverage and much data exhibited similar stock status to those based on Japanese abundance indices (**JPE-JPL)**. The stock assessment results based on the SPC observed longline (**JPE-SPC**) had large uncertainties because of the large fluctuations of the observed CPUE in additions to the lacking of the data in the most recent years after 2009. The stock assessment results based on the Hawaii longline (**JPE-HWI**) showed a slightly decline in 2000s, however, the stock biomass recovered around MSY level in the most recent years (2012-2014). These results supported the conclusion of the stock status (i.e. not overfishing and not overfished) for the North Pacific blue shark.

Time series of relative values and Kobe-plots showed large uncertainties for several reference cases **(Figs.5, 7** and **Fig. A5**). This was probably due to the uncertainties (i.e. inconsistent trends between CPUE and catch) in the CPUE time series. If we use relative values (B/ B_{MSY} and H/ H_{MSY}) estimated from the fixed MSY based reference points (B_{MSY} and H_{MSY}), the credible intervals become wider, while if we use relative values predicted from the MCMC samples, the credible intervals become narrower (see **Fig. 11**) because the relative values were directly predicted from the process of the MCMC samples. The former case does not allow to give the reliable credible intervals, whereas the latter case causes a difficulty for manager to understand the meaning of the reference points due to the unfixed reference points. In this study, we chose to use the latter case because the wider credible intervals have more impact on the decision making of the management than the difficulty in the understanding of the unfixed reference points.

In the previous stock assessment, ISC (2014) evaluated the impacts of the priors in the sensitivity runs using a Bayes factor. In this study, we used the WAIC as the information criterion of the evaluation for the model (Watanabe 2010). WAIC is an information criterion to evaluate the goodness of the model's prediction, and it has the same role as AIC as a frequentism. The smallest value of the WAIC indicates the best performance of the prediction that enables to distinctly evaluate the model.

Comparisons of B/B_{MSY} and H/H_{MSY} between previous (2014) and current (2017) stock assessment results showed similar trends for **JPE-JPL** but different trends for other three reference cases (**JPE-HWI**, **JPE-SPC**, **JPE-TWN**) (**Fig. A8**). Probably these were due to not only the changes in each CPUE trends between previous (2014) and current (2017) stock assessment but also

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the additional recent year's data because the time span of the other three CPUEs were shorter than that of **JPL**.

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Table 1. Time series of catch (total dead removals; tons) for different countries/groups.

Year	Canada	China	IATTC	Japan	Korea	Mexico	Non-ISC	Taiwan	USA	Total
1,971	0	0	7	23,252	0	440	0	12,070	30	35,799
1,972	0	0	5	17,977	0	440	0	15,056	30	33,508
1,973	0	0	5	25,328	0	440	0	12,025	30	37,828
1,974	0	0	5	23,546	0	440	0	10,742	30	34,763
1,975	0	0	7	30,277	5	440	0	9,392	33	40,154
1,976	0	0	7	43,026	32	374	0	10,286	129	53,854
1,977	0	0	6	55,144	55	386	0	10,045	225	65,861
1,978	0	0	8	48,550	17	561	0	10,603	329	60,068
1,979	1	0	10	57,193	0	338	0	12,360	466	70,368
1,980	11	0	10	59,773	114	624	0	12,840	630	74,002
1,981	0	0	9	74,573	0	1,593	0	10,961	669	87,805
1,982	0	0	6	57,189	242	1,181	0	12,003	784	71,405
1,983	25	0	6	55,408	27	1,548	0	10,586	954	68,554
1,984	0	0	6	52,161	88	390	0	9,509	1,112	63,266
1,985	60	0	3	48,314	145	528	0	10,712	1,291	61,053
1,986	90	0	2	44,165	95	2,128	0	9,048	1,496	57,024
1,987	159	0	2	39,996	159	2,205	0	6,729	1,508	50,758
1,988	0	0	6	43,321	140	3,337	0	6,966	1,783	55,553
1,989	0	0	5	52,206	49	1,643	0	7,897	1,607	63,407
1,990	4	0	3	33,933	58	2,865	0	8,885	1,855	47,603
1,991	0	0	2	35,452	65	3,197	0	9,619	1,763	50,098
1,992	0	0	3	28,655	49	3,085	0	7,615	2,328	41,735
1,993	0	0	3	26,667	28	3,517	0	6,919	3,747	40,881
1,994	0	0	2	34,519	33	1,758	0	5,470	2,723	44,505
1,995	0	0	10	38,478	104	2,100	161	10,100	2,165	53,118
1,996	1	0	2	29,843	231	3,117	165	9,917	2,586	45,862
1,997	1	0	4	33,276	433	2,948	261	13,773	3,020	53,716
1,998	2	0	2	31,621	623	3,134	634	11,640	3,103	50,759
1,999	1	0	1	28,379	471	2,261	782	14,118	2,960	48,973
2,000	1	0	2	30,928	433	2,719	1,350	20,391	1,378	57,202
2,001	5	340	0	31,738	163	2,587	944	9,831	381	45,989
2,002	5	334	3	27,485	293	2,524	2,126	11,582	273	44,625
2,003	17	305	1	28,661	399	2,307	1,708	10,244	281	43,923
2,004	4	282	1	27,285	50	3,781	5,846	12,668	201	50,118
2,005	0	343	0	30,929	44	2,721	3,081	14,478	146	51,742
2,006	20	201	3	26,526	21	2,765	3,111	14,175	143	46,965
2,007	9	234	2	25,134	203	3,324	3,153	13,848	182	46,089
2,008	6	134	3	21,201	75	4,355	2,066	14,824	138	42,802
2,009	8	298	2	20,688	146	4,423	1,778	16,559	122	44,024
2,010	7	357	1	23,670	470	4,469	1,808	13,349	150	44,281
2,011	13	613	1	21,006	952	3,719	2,624	16,451	142	45,521
2,012	9	758	2	14,975	551	4,108	2,778	16,451	145	39,777
2,013	26	598	2	18,319	491	4,494	2,131	7,534	268	33,863
2,014	9	251	0	17,306	328	5,502	2,059	11,856	396	37,707
2,015	23	627	0	14,111	121	5,502	2,059	10,042	471	32,956

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Table 2. CPUE time series (relative value to its mean) for different fleets and the coefficient of variations (CV). **JPE:** Japanese offshore shallow-set longline (1976-1993), **JPL**: Japanese offshore shallow-set longline (1994-2015), **HWI**: Hawaii deep-set longline (2000-2015), **MEX:** Mexico longline (2006-2015), **SPC:** SPC observed longline (1993-2009), and **TWN:** Taiwan large-scale longline (2004-2015

Year	JPE-JPL		HWI		MEX		SPC		TWN	
	CPUE	CV	CPUE	CV	CPUE	CV	CPUE	CV	CPUE	CV
1976	1.35	0.10								
1977	1.40	0.10								
1978	1.21	0.10								
1979	1.27	0.10								
1980	1.36	0.10								
1981	1.13	0.10								
1982	1.11	0.10								
1983	1.05	0.10								
1984	0.91	0.10								
1985	0.78	0.10								
1986	0.91	0.10								
1987	0.68	0.10								
1988	0.71	0.10								
1989	0.64	0.10								
1990	0.67	0.10								
1991	0.85	0.10								
1992	0.89	0.10								
1993	1.07	0.10					0.87	0.14		
1994	0.72	0.10					0.96	0.14		
1995	0.84	0.10					0.46	0.14		
1996	0.80	0.10					0.87	0.14		
1997	0.97	0.10					1.18	0.14		
1998	0.98	0.10					1.80	0.14		
1999	1.05	0.10					1.50	0.14		
2000	1.05	0.10	1.97	0.29			1.35	0.14		
2001	1.19	0.10	1.12	0.29			1.37	0.14		
2002	1.17	0.10	0.82	0.29			1.06	0.14		
2003	1.26	0.10	1.30	0.29			0.85	0.14		
2004	1.12	0.10	1.20	0.29			1.05	0.14	0.24	0.10
2005	1.25	0.10	0.84	0.29			0.79	0.14	1.58	0.10
2006	1.10	0.10	0.79	0.29	1.23	0.12	0.85	0.14	0.88	0.10
2007	0.90	0.10	1.00	0.29	1.17	0.12	0.80	0.14	0.56	0.10
2008	0.84	0.10	0.56	0.29	1.49	0.12	0.69	0.14	0.85	0.10
2009	1.07	0.10	0.73	0.29	1.09	0.12	0.57	0.14	0.42	0.10
2010	1.05	0.10	0.83	0.29	0.83	0.12			1.19	0.10
2011	0.83	0.10	0.91	0.29	0.66	0.12			1.10	0.10
2012	0.96	0.10	0.75	0.29	0.81	0.12			1.36	0.10
2013	0.88	0.10	0.84	0.29	1.22	0.12			1.09	0.10
2014	0.87	0.10	1.01	0.29	0.83	0.12			1.27	0.10
2015	1.10	0.10	1.34	0.29	0.64	0.12			1.45	0.10

Table 3. Summaries of parameters for the **base-parameter model**.

No	Parameters	Symbol	Unit	Reference value	Alternative runs/Parameter ranges
1	Priors of unfished biomass	K	1000 tons	Uniform distribution on log (K)	100 - 20000
2	Prior means for intrinsic rate of population biomass	r	per year	0.221	0.187, 0.34
3	Standard deviation of prior r	σ_r		0.5	0.3, 0.7
4	Prior means for the ratio of initial biomass to unfished biomass	φ $(=B_{1971}/K)$		0.8	0.5, 1.0
5	Standard deviation of prior φ	σ_φ		0.5	0.7, 0.9
6	Shape parameter	m $(=B_{MSY}/K)$		0.55	0.47, 0.58, try to estimate
7	Process error	η		(SD =) 0.07	try to estimate
8	Observation error*	ε		(CV =)	
9	Pair combinations	r vs φ		0.221 vs 0.8	0.187 vs 0.5, 0.187 vs 1.0, 0.34 vs 0.5, 0.34 vs 1.0
10	Pair combinations	r vs m		0.221 vs 0.55	0.187 vs 0.47, 0.187 vs 0.58, 0.34 vs 0.47, 0.34 vs 0.58
11	Prior means for r estimated from different M- schedules	r	per year		See Table A1

*CV is estimated from the observed CV of abundance indices for each fleet outside the model by the Francis methods (2011)

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Table 4. Model selections based on WAIC from sensitivity runs for various combinations of CPUE time series included in the model. Grey shade indicates the minimum value of WAIC for each combination of CPUE explored. WAIC values should be compared only within a single column and not between columns.

Parameters and variables	Conditions	WAIC									
		JPE-JPL	JPE-HWI	JPE-MEX	JPE-SPC	JPE-TWN	JPL	HWI	MEX	SPC	TWN
Basecase		263.71	265.25	286.79	290.4115	419.92	261.61	244.64	307.13	314.92	572.99
r	Low	262.89	264.49	286.43	290.2927	419.01	259.96	244.19	307.80	314.82	574.99
	High	262.80	264.77	287.21	291.7898	421.14	261.72	244.69	309.65	316	576.28
σ_{φ}	Low	262.86	264.27	286.93	289.7826	420.86	260.51	246.16	309.13	315.74	570.24
	High	262.54	264.11	287.48	290.4071	424.64	259.86	244.98	306.77	315.1	574.06
φ (=B_{1971}/K)	Low	262.66	264.95	287.31	291.2253	414.35	259.46	245.18	306.56	316.81	561.63
	High	263.31	264.27	286.91	290.4303	422.75	261.05	245.52	306.60	315.53	578.07
σ_{φ}	Low	263.32	265.12	287.45	291.7799	415.00	259.76	245.42	308.15	316.63	562.24
	High	263.22	265.47	286.90	289.8938	413.37	261.11	245.23	309.20	314.93	558.67
m (= B_{MSY}/K)	Low	262.79	264.96	288.16	291.3106	424.89	260.37	244.5	308.22	316.08	580.61
	High	263.14	264.51	286.60	290.4705	420.95	259.93	245.18	307.43	314.87	571.21
η	Estimate	285.55	288.29	293.74	293.8884	290.59	285.41	294.6	300.08	302.3	293.89
r vs φ	Low vs Low	263.52	265.69	286.03	290.4588	415.40	260.94	244.28	307.60	315.95	567.44
	Low vs High	263.33	264.71	287.06	290.1034	419.27	261.04	245.66	306.89	315.86	575.45
	High vs Low	262.51	264.71	287.35	292.0278	418.10	261.26	245.57	310.10	317.36	560.59
	High vs High	262.51	264.71	287.35	292.0278	418.10	261.26	245.57	310.10	317.36	560.59
r vs m	Low vs Low	263.75	264.62	287.21	290.5412	420.86	260.58	245.97	308.00	315.11	577.68
	Low vs High	263.83	265.03	286.41	291.2145	418.82	260.20	245.36	305.27	313.98	571.43
	High vs Low	262.42	264.40	287.93	290.9741	423.18	261.79	244.98	310.70	317.69	574.14
	High vs High	262.69	264.92	287.51	291.0638	419.64	261.47	244.87	309.26	317.56	572.32
r from different-M	Scenario-1	262.92	264.32	286.31	291.0861	421.29	260.86	244.59	308.04	314.17	575.11
	Scenario-2	263.25	264.62	286.69	290.799	420.24	261.37	244.85	307.70	314.13	573.67
	Scenario-3	263.71	265.25	286.79	290.4115	419.92	261.61	244.64	307.13	314.92	572.99
	Scenario-4	262.89	264.49	286.43	290.2927	419.01	259.96	244.19	307.80	314.82	574.99
	Scenario-5	262.41	264.81	287.15	290.8653	420.73	259.86	245.23	309.77	314.23	573.51
	Scenario-6	262.92	264.32	286.31	291.0861	421.29	260.86	244.59	308.04	314.17	575.11
	Scenario-7	262.66	265.18	287.47	291.3779	421.58	261.26	244.23	312.24	317.82	575.56
	Scenario-8	263.15	265.41	288.39	290.5078	425.81	261.81	245.38	310.95	317.07	577.64

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Table 5. Median and the CV from the predicted posterior distributions of key parameters and variables for 10 reference cases and prior-only run, where **JPE:** Japanese offshore shallow-set longline (1976-1993), **JPL**: Japanese offshore shallow-set longline (1994-2015), **HWI**: Hawaii deep-set longline (2000-2015), **MEX:** Mexico longline (2006-2015), **SPC:** SPC observed longline (1993-2009), and **TWN:** Taiwan large-scale longline (2004-2015). A) **Base-parameter model** and B) **Best-parameter model**.

A)

Parameters and variables	JPE-JPL		JPE-HWI		JPE-MEX		JPE-SPC		JPE-TWN		JPL		HWI		MEX		SPC		TWN		Prior-only	
	Median	CV	Median	CV	Median	CV	Median	CV	Median	CV	Median	CV	Median	CV	Median	CV	Median	CV	Median	CV	Median	CV
r	0.33	0.42	0.26	0.46	0.17	0.44	0.22	0.43	0.17	0.44	0.19	0.45	0.22	0.56	0.14	0.48	0.16	0.44	0.17	0.44	0.20	0.58
K (1000 tons)	842	0.56	964	0.51	1,218	0.49	1,081	0.62	3,117	0.83	2,496	1.01	2,492	1.00	1,664	0.98	1,805	1.10	3,117	0.83	8,016	0.63
MSY (1000 tons)	60	0.18	53	0.19	46	0.24	52	0.28	113	0.54	96	1.04	108	1.30	48	1.27	59	1.05	113	0.54	317	0.95
B_{MSY} (1000 tons)	463	0.56	530	0.51	670	0.49	595	0.62	1,715	0.83	1,373	1.01	1,371	1.00	915	0.98	993	1.10	1,715	0.83	4,410	0.63
B_{1971} (1000 tons)	627	0.64	757	0.52	905	0.40	848	0.65	768	1.05	1,489	1.09	1,616	1.08	1,184	1.02	1,221	1.15	768	1.05	4,588	0.75
B_{2015} (1000 tons)	599	0.59	495	0.55	262	0.64	515	0.79	2,467	0.90	2,002	1.08	1,984	1.11	348	1.76	893	1.44	2,467	0.90	7,231	0.67
B_{2015}/B_{MSY}	1.34	0.14	0.97	0.34	0.38	0.55	0.91	0.35	1.55	0.20	1.50	0.17	1.54	0.29	0.42	0.68	1.00	0.44	1.55	0.20	1.66	0.17
B_{2015}/B_{1971}	0.98	0.30	0.68	0.42	0.30	0.52	0.63	0.39	3.26	0.49	1.32	0.49	1.19	0.54	0.32	0.87	0.74	0.63	3.26	0.49	1.41	0.49
B_{2015}/K	0.74	0.14	0.53	0.34	0.21	0.55	0.50	0.35	0.85	0.20	0.82	0.17	0.85	0.29	0.23	0.68	0.55	0.44	0.85	0.20	0.92	0.17
H_{MSY}	0.13	0.42	0.10	0.46	0.07	0.44	0.09	0.43	0.07	0.44	0.07	0.45	0.08	0.56	0.06	0.48	0.06	0.44	0.07	0.44	0.08	0.58
H_{1971}	0.06	0.56	0.05	0.52	0.04	0.41	0.04	0.47	0.05	0.66	0.02	0.79	0.02	0.85	0.03	0.51	0.03	0.61	0.05	0.66	0.01	1.12
H_{2015}	0.06	0.41	0.07	0.45	0.13	0.46	0.06	0.61	0.01	0.67	0.02	0.85	0.02	1.47	0.09	0.68	0.04	1.57	0.01	0.67	0.00	2.33
H_{2015}/H_{1971}	0.94	0.27	1.36	0.41	3.10	0.40	1.47	0.47	0.28	0.53	0.70	0.41	0.77	1.05	2.84	0.59	1.24	1.16	0.28	0.53	0.66	0.85
H_{2015}/H_{MSY}	0.41	0.26	0.67	0.50	1.94	0.46	0.71	0.66	0.20	0.43	0.23	0.71	0.19	1.94	1.88	0.71	0.56	1.45	0.20	0.43	0.06	3.09

B)

Parameters and variables	JPE-JPL		JPE-HWI		JPE-MEX		JPE-SPC		JPE-TWN		JPL		HWI		MEX		SPC		TWN	
	Median	CV	Median	CV	Median	CV	Median	CV	Median	CV	Median	CV	Median	CV	Median	CV	Median	CV	Median	CV
r	0.50	0.32	0.28	0.60	0.14	0.49	0.22	0.29	0.24	0.52	0.19	0.44	0.25	0.56	0.15	0.52	0.16	0.46	0.17	0.52
K (1000 tons)	570	0.38	890	0.83	1640	0.70	1083	0.34	1271	0.86	2814	0.94	2311	1.03	3397	0.89	3734	0.85	3269	0.90
MSY (1000 tons)	61	0.10	54	0.21	50	0.39	52	0.20	66	0.50	106	0.92	118	1.29	103	0.93	116	0.87	112	0.90
B_{MSY} (1000 tons)	314	0.38	490	0.83	902	0.70	596	0.34	699	0.86	1548	0.94	1272	1.03	1869	0.89	2054	0.85	1798	0.90
B_{1971} (1000 tons)	412	0.50	700	0.79	916	0.41	844	0.38	785	0.85	1210	1.04	1548	1.10	1898	0.98	2035	0.96	1788	1.01
B_{2015} (1000 tons)	425	0.40	469	0.83	275	0.60	518	0.50	888	0.89	2198	1.01	1933	1.12	603	1.31	1003	1.27	1981	1.05
B_{2015}/B_{MSY}	1.38	0.11	1.02	0.36	0.30	0.63	0.90	0.34	1.36	0.30	1.48	0.20	1.58	0.24	0.41	0.68	0.55	0.71	1.29	0.38
B_{2015}/B_{1971}	1.05	0.33	0.71	0.45	0.31	0.51	0.62	0.37	1.14	0.50	1.82	0.52	1.23	0.50	0.38	0.83	0.52	0.89	1.16	0.60
B_{2015}/K	0.76	0.11	0.56	0.36	0.17	0.63	0.50	0.34	0.75	0.30	0.82	0.20	0.87	0.24	0.23	0.68	0.30	0.71	0.71	0.38
H_{MSY}	0.19	0.32	0.11	0.60	0.05	0.49	0.09	0.29	0.09	0.52	0.07	0.44	0.10	0.56	0.06	0.52	0.06	0.46	0.07	0.52
H_{1971}	0.09	0.49	0.05	0.66	0.04	0.44	0.04	0.37	0.05	0.65	0.03	0.78	0.02	0.88	0.02	0.89	0.02	0.91	0.02	0.90
H_{2015}	0.08	0.31	0.07	0.46	0.12	0.43	0.06	0.69	0.04	0.64	0.01	0.84	0.02	1.28	0.05	0.87	0.03	1.58	0.02	0.93
H_{2015}/H_{1971}	0.87	0.29	1.30	0.44	2.98	0.39	1.48	0.51	0.81	0.55	0.51	0.49	0.75	0.85	2.44	1.14	1.77	1.31	0.79	0.90
H_{2015}/H_{MSY}	0.40	0.18	0.62	0.59	2.27	0.45	0.72	0.69	0.37	0.62	0.21	0.75	0.17	1.73	0.89	0.98	0.54	1.70	0.25	0.94

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Table 6. The summary of sensitivity runs that the values were calculated from the predicted posterior distributions of key parameters and variables for JPE-JPL. Bolds denote the values of the Base-parameter model and Best-parameter model selected by WAIC.

Parameters and variables	Conditions	r			K (1000 tons)			B_{MSY} (1000 tons)			H_{MSY}			B_{2015}/B_{MSY}			H_{2015}/H_{MSY}		
		2.5%	50%	97.5%	2.5%	50%	97.5%	2.5%	50%	97.5%	2.5%	50%	97.5%	2.5%	50%	97.5%	2.5%	50%	97.5%
Base-parameter model		**0.12**	**0.33**	**0.70**	**407**	**842**	**2435**	**224**	**463**	**1340**	**0.05**	**0.13**	**0.27**	**0.90**	**1.34**	**1.66**	**0.25**	**0.41**	**0.71**
r	Low	0.10	0.28	0.63	455	979	3353	250	539	1845	0.04	0.11	0.24	0.82	1.32	1.67	0.24	0.42	0.77
	High	0.18	0.44	0.82	353	638	1627	194	351	895	0.07	0.17	0.32	1.00	1.37	1.64	0.28	0.40	0.62
σ_{φ}	Low	0.14	0.26	0.46	599	1057	2305	330	582	1268	0.06	0.10	0.18	0.85	1.31	1.67	0.24	0.43	0.73
	High	0.11	0.39	0.83	346	726	2813	190	400	1547	0.04	0.15	0.32	0.91	1.35	1.64	0.26	0.41	0.70
φ (=B_{1971}/K)	Low	0.11	0.34	0.71	405	842	2865	223	463	1576	0.04	0.13	0.27	0.69	1.31	1.63	0.27	0.42	0.78
	High	0.13	0.33	0.69	411	834	2425	226	459	1334	0.05	0.13	0.27	0.94	1.35	1.66	0.25	0.41	0.69
σ_{φ}	Low	0.12	0.32	0.67	424	871	2552	233	479	1404	0.05	0.12	0.26	0.86	1.33	1.66	0.25	0.42	0.73
	High	0.13	0.34	0.71	407	833	2323	224	458	1278	0.05	0.13	0.27	0.88	1.34	1.66	0.26	0.41	0.71
m (= B_{MSY}/K)	Low	0.13	0.31	0.57	383	704	1817	180	331	854	0.07	0.18	0.33	1.01	1.46	1.84	0.24	0.38	0.62
	High	0.12	0.33	0.72	445	964	2903	258	559	1684	0.04	0.11	0.24	0.81	1.29	1.60	0.25	0.43	0.77
η	Estimate	0.10	0.27	0.65	454	1134	4282	250	624	2356	0.04	0.10	0.25	0.76	1.41	1.78	0.16	0.37	0.73
r vs φ	Low vs Low	0.10	0.30	0.66	431	948	3316	237	521	1824	0.04	0.11	0.26	0.65	1.30	1.64	0.26	0.43	0.81
	Low vs High	0.11	0.29	0.62	453	948	2833	249	521	1558	0.04	0.11	0.24	0.88	1.34	1.66	0.24	0.42	0.74
	High vs Low	0.18	0.45	0.84	347	629	1655	191	346	910	0.07	0.17	0.32	0.96	1.36	1.63	0.28	0.40	0.62
	High vs High	0.18	0.45	0.84	347	629	1655	191	346	910	0.07	0.17	0.32	0.96	1.36	1.63	0.28	0.40	0.62
r vs m	Low vs Low	0.11	0.27	0.53	412	785	2044	194	369	961	0.06	0.16	0.31	0.96	1.45	1.85	0.24	0.39	0.66
	Low vs High	0.10	0.29	0.66	473	1089	3409	274	632	1977	0.03	0.09	0.22	0.79	1.28	1.60	0.24	0.44	0.81
	High vs Low	0.17	0.38	0.65	340	576	1286	160	271	605	0.10	0.22	0.38	1.11	1.49	1.82	0.26	0.37	0.55
	High vs High	0.18	0.46	0.89	360	691	1858	209	401	1078	0.06	0.15	0.29	0.98	1.32	1.60	0.28	0.41	0.64
r from different-M	Scenario-1	0.11	0.31	0.66	434	894	3242	239	492	1784	0.04	0.12	0.25	0.82	1.33	1.66	0.22	0.42	0.74
	Scenario-2	0.10	0.26	0.61	463	1050	3060	255	578	1683	0.04	0.10	0.23	0.75	1.31	1.66	0.26	0.43	0.81
	Scenario-3	0.12	0.33	0.70	407	842	2435	224	463	1340	0.05	0.13	0.27	0.90	1.34	1.66	0.25	0.41	0.71
	Scenario-4	0.10	0.28	0.63	455	979	3353	250	539	1845	0.04	0.11	0.24	0.82	1.32	1.67	0.24	0.42	0.77
	Scenario-5	**0.13**	**0.35**	**0.71**	**405**	**797**	**2329**	**223**	**439**	**1281**	**0.05**	**0.14**	**0.27**	**0.90**	**1.34**	**1.66**	**0.26**	**0.41**	**0.69**
	Scenario-6	0.11	0.31	0.66	434	894	3242	239	492	1784	0.04	0.12	0.25	0.82	1.33	1.66	0.22	0.42	0.74
	Scenario-7	0.24	0.50	0.88	329	570	1240	181	314	682	0.09	0.19	0.34	1.07	1.38	1.64	0.29	0.40	0.58
	Scenario-8	0.21	0.48	0.86	339	596	1455	187	328	801	0.08	0.18	0.33	1.05	1.37	1.65	0.28	0.40	0.59

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Table 7. Projected trajectory of biomass and catch based on **base-parameter model** under alternative harvest scenarios for 5 reference cases. Green blocks indicate the projection is greater than MSY level (see table 4).

A) Biomass (tons)

Fleet	Harvest scenario	Biomass (1000 tons)										
		2015	2016	2017	2018	2019	2020	2021	2022	2023	2024	Average
JAE-JAL	1: High-H (+ 20%)	576	581	585	588	591	594	596	598	599	600	591
	2: H_{MSY}	576	553	537	525	515	507	500	495	490	486	518
	3: $H_{2012\text{-}2014}$	576	589	599	608	616	621	626	630	633	636	613
	4: Low-H (- 20%)	576	596	613	628	640	650	657	663	668	673	636
JAE-HWI	1: High-H (+ 20%)	486	484	482	481	479	478	477	477	475	474	479
	2: H_{MSY}	486	478	475	473	473	474	475	477	479	480	477
	3: $H_{2012\text{-}2014}$	486	492	497	502	506	510	513	515	518	521	506
	4: Low-H (- 20%)	486	500	512	523	533	542	550	558	565	571	534
JAE-MEX	1: High-H (+ 20%)	276	261	245	232	220	208	197	186	176	167	217
	2: H_{MSY}	276	284	292	300	308	316	324	331	339	347	312
	3: $H_{2012\text{-}2014}$	276	267	259	251	243	236	228	222	215	209	241
	4: Low-H (- 20%)	276	274	272	270	268	266	265	263	261	260	268
JAE-SPC	1: High-H (+ 20%)	514	515	514	514	514	514	515	515	514	514	514
	2: H_{MSY}	514	513	512	512	513	514	516	518	519	522	515
	3: $H_{2012\text{-}2014}$	514	523	529	535	541	547	552	556	560	563	542
	4: Low-H (- 20%)	514	530	544	557	570	580	590	600	608	615	571
JAE-TWN	1: High-H (+ 20%)	2370	2400	2426	2451	2478	2498	2520	2541	2555	2572	2481
	2: H_{MSY}	2370	2286	2218	2163	2121	2085	2047	2020	1993	1970	2127
	3: $H_{2012\text{-}2014}$	2370	2407	2442	2472	2504	2530	2559	2580	2600	2623	2509
	4: Low-H (- 20%)	2370	2415	2457	2495	2533	2562	2598	2623	2648	2672	2537

B) Catch(tons)

Fleet	Harvest scenario	Catch (1000 tons)										
		2015	2016	2017	2018	2019	2020	2021	2022	2023	2024	Average
JAE-JAL	1: High-H (+ 20%)	46.6	46.9	47.2	47.5	47.7	47.9	48.0	48.1	48.2	48.3	48
	2: H_{MSY}	76.8	72.7	69.8	67.8	66.2	65.0	64.1	63.4	62.8	62.3	67
	3: $H_{2012\text{-}2014}$	38.8	39.6	40.3	40.9	41.3	41.7	41.9	42.2	42.3	42.5	41
	4: Low-H (- 20%)	31.0	32.1	33.0	33.7	34.3	34.7	35.1	35.4	35.6	35.8	34
JAE-HWI	1: High-H (+ 20%)	47.2	47.1	47.0	46.9	46.9	46.9	46.9	46.8	46.8	46.8	47
	2: H_{MSY}	48.7	48.9	49.1	49.4	49.6	49.8	50.0	50.1	50.2	50.3	50
	3: $H_{2012\text{-}2014}$	39.3	39.9	40.3	40.7	41.1	41.5	41.8	42.0	42.3	42.5	41
	4: Low-H (- 20%)	31.5	32.4	33.2	33.9	34.6	35.2	35.7	36.2	36.7	37.1	35
JAE-MEX	1: High-H (+ 20%)	41.3	39.0	36.8	34.8	33.0	31.2	29.6	28.1	26.6	25.2	33
	2: H_{MSY}	17.8	18.4	19.1	19.8	20.4	21.1	21.9	22.6	23.2	23.9	21
	3: $H_{2012\text{-}2014}$	34.4	33.4	32.4	31.4	30.5	29.7	28.8	28.0	27.3	26.5	30
	4: Low-H (- 20%)	27.5	27.4	27.3	27.2	27.1	27.0	26.9	26.8	26.7	26.6	27
JAE-SPC	1: High-H (+ 20%)	46.3	46.4	46.6	46.7	46.8	46.9	47.0	47.0	47.1	47.1	47
	2: H_{MSY}	46.1	46.6	46.9	47.3	47.6	47.8	48.0	48.3	48.5	48.7	48
	3: $H_{2012\text{-}2014}$	38.6	39.3	39.8	40.3	40.8	41.3	41.6	42.0	42.3	42.6	41
	4: Low-H (- 20%)	30.9	31.8	32.7	33.5	34.2	34.9	35.4	36.0	36.5	37.0	34
JAE-TWN	1: High-H (+ 20%)	47.4	47.8	48.1	48.4	48.7	48.9	49.1	49.3	49.5	49.6	49
	2: H_{MSY}	159.9	153.0	147.7	143.7	140.3	137.3	135.3	133.2	131.6	130.0	141
	3: $H_{2012\text{-}2014}$	39.5	39.9	40.4	40.7	41.0	41.3	41.5	41.7	41.9	42.1	41
	4: Low-H (- 20%)	31.6	32.1	32.5	32.9	33.2	33.5	33.7	33.9	34.1	34.3	33

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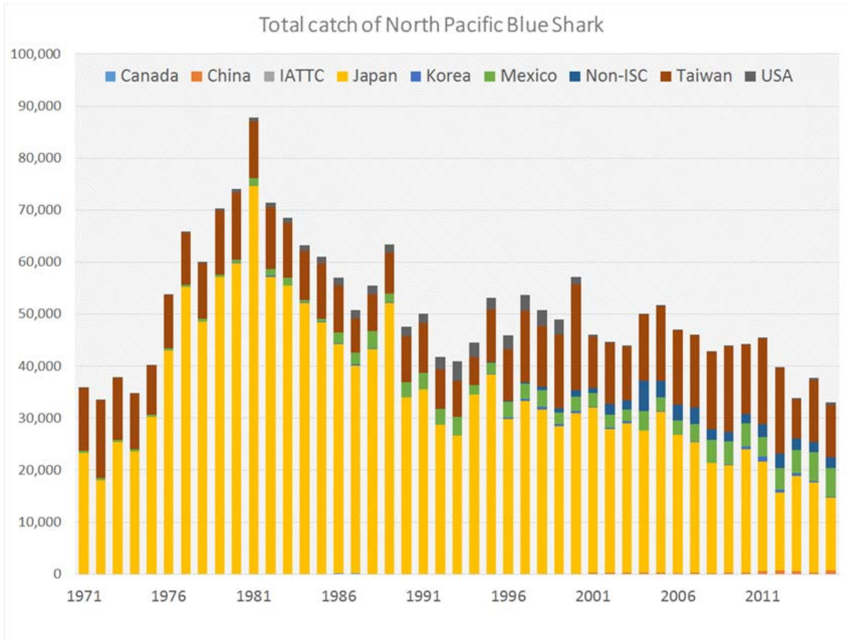

Fig. 1 Fleet specific total amount (total dead removals) of blue shark's catch (tons) caught in the North Pacific during 1971 and 2015.

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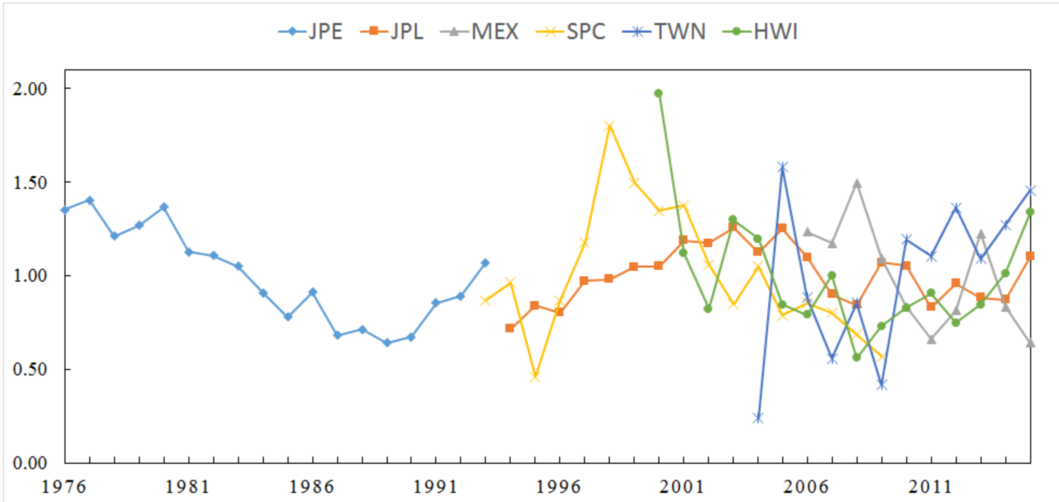

Fig. 2 Yearly changes in standardized CPUE (Japanese offshore shallow-set longline: **JPE**) of North Pacific blue shark during 1976 and 1993, and five standardized CPUE (Hawaii deep-set longline: **HWI**, Japanese offshore shallow-set longline: **JPL**, Mexico longline: **MEX**, SPC observed longline: **SPC**, Taiwan large-scale longline: **TWN**) of blue shark during 1994 and 2015

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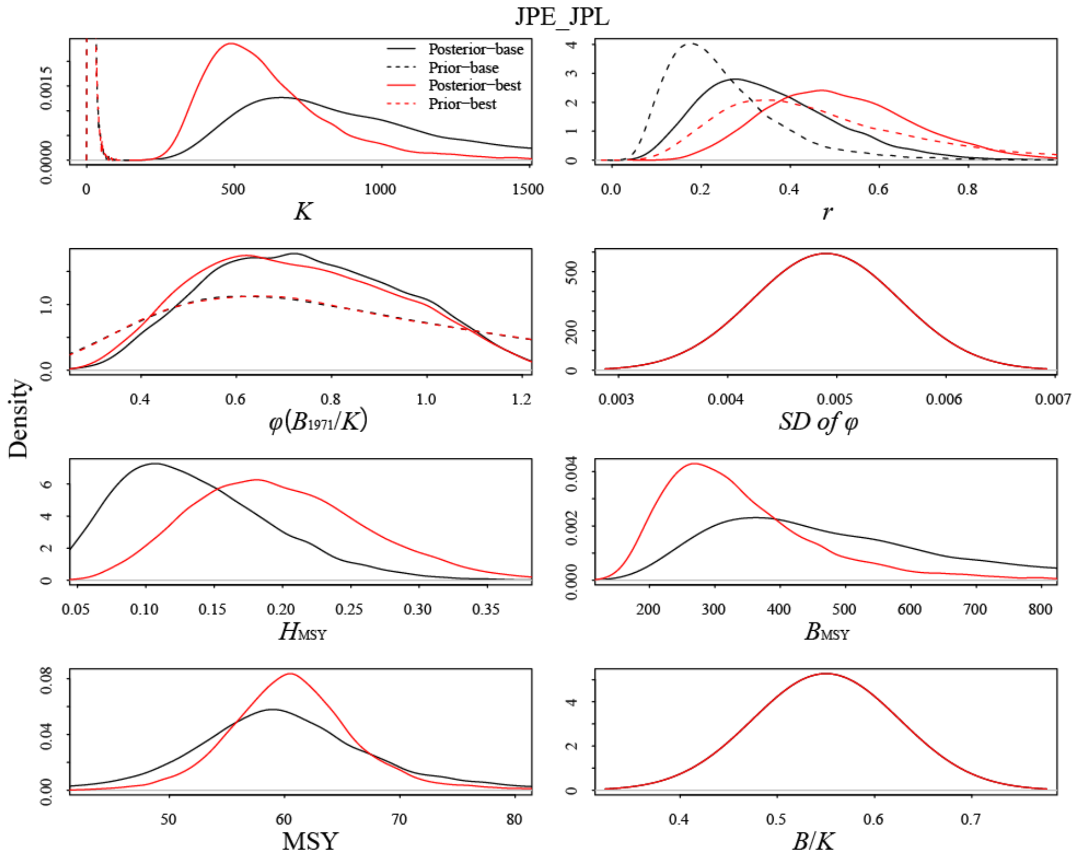

Fig. 3 Marginal posterior distributions (solid line) of key parameters (K, r,) and variables (φ=B_{1971}/K:psi, SD of φ, H_{MSY}, B_{MSY}, MSY, B_{MSY}/K) for **base-parameter model** and **best-parameter model**. Dotted line indicates the prior distributions. Black and red lines denote the prior and posterior distributions of base-parameters and best-parameters respectively.

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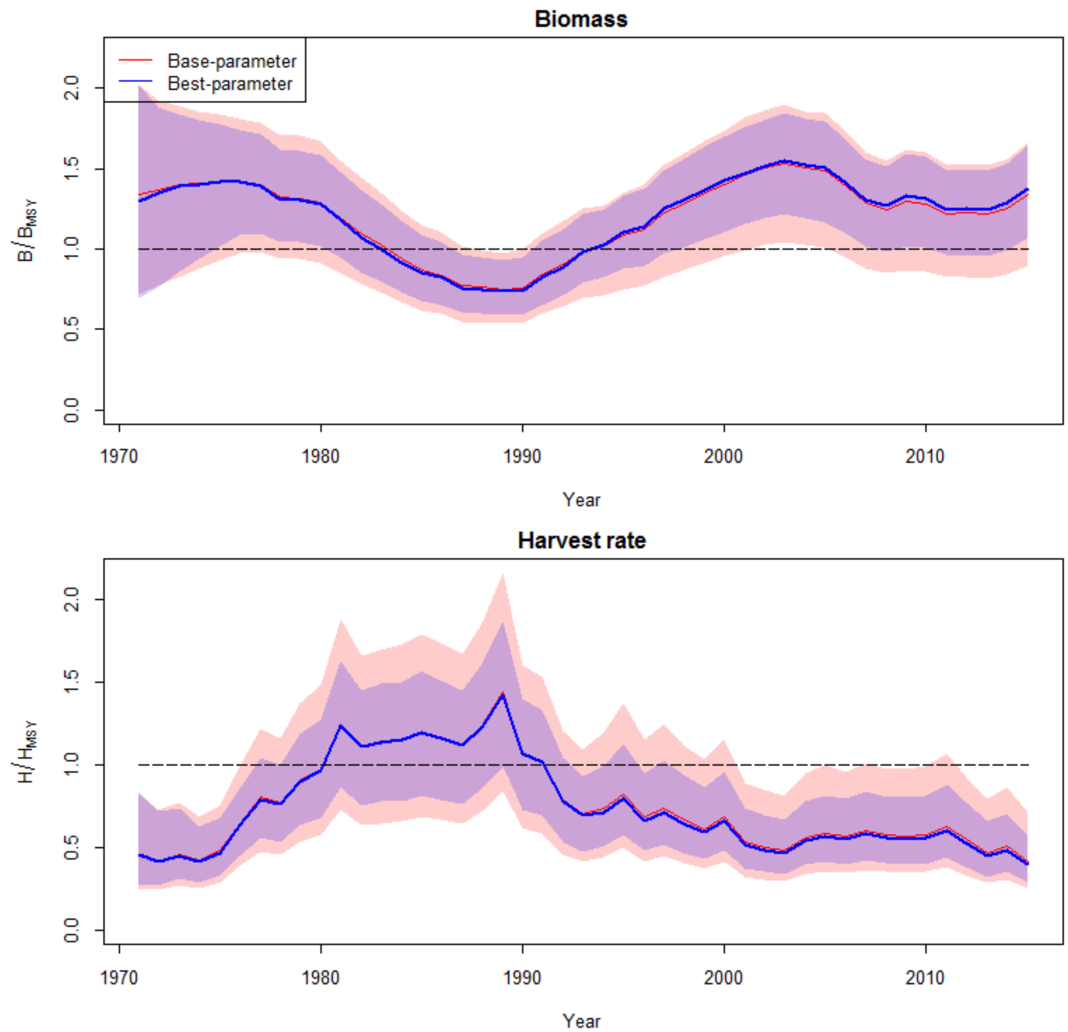

Fig. 4 Comparisons of yearly changes in median estimate of B/B_{MSY} and H/H_{MSY} between **base-parameter model** (red line) and **best-parameter model** (blue line) for JPE-JPL. Shadow denotes 95% credible interval. The horizontal dashed line indicates the median estimate for the biomass and harvest rate at the maximum sustainable yield (B_{MSY} and H_{MSY}).

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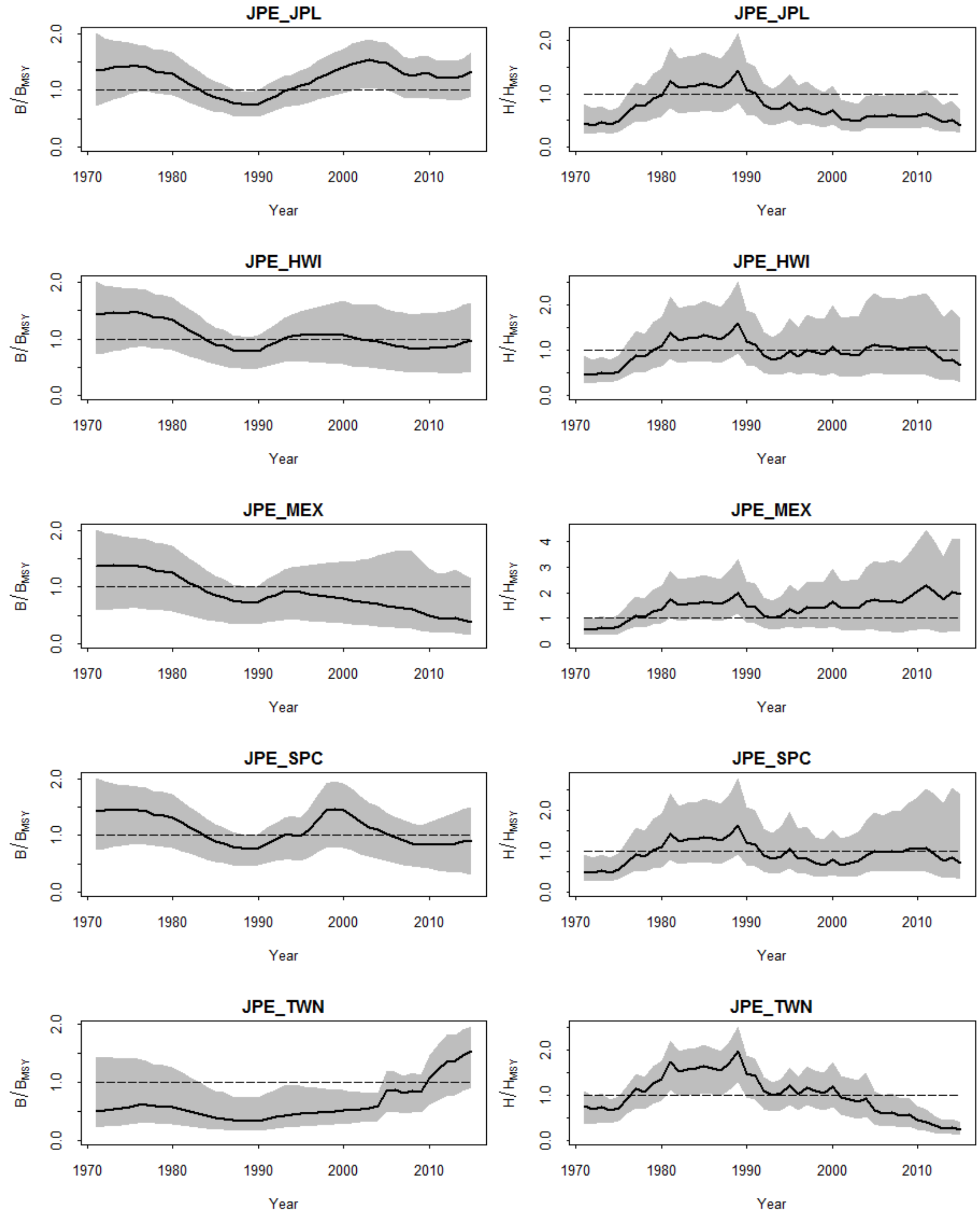

Fig. 5 Historical trajectories of median estimate based on **base-parameter model** and the 95% credible intervals (grey shadow) for 5 reference cases. The horizontal dashed line indicates the median estimate for the biomass and harvest rate at the maximum sustainable yield (B_{MSY} and H_{MSY}).

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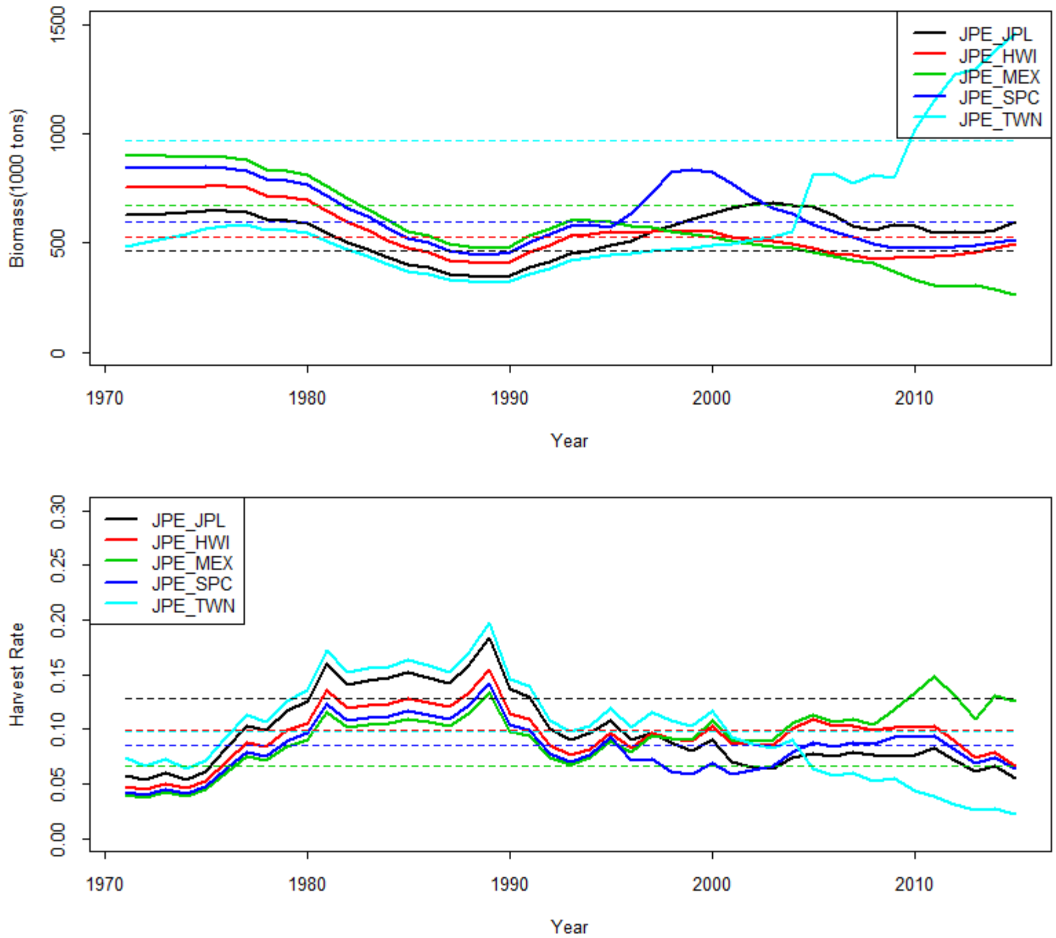

Fig. 6 Historical trajectories of median estimates based on **base-parameter model** for biomass (1000 tons) and harvest rate among 5 reference cases. The horizontal dashed line indicates the median estimate for the biomass and harvest rate at the maximum sustainable yield (B_{MSY} and H_{MSY}).

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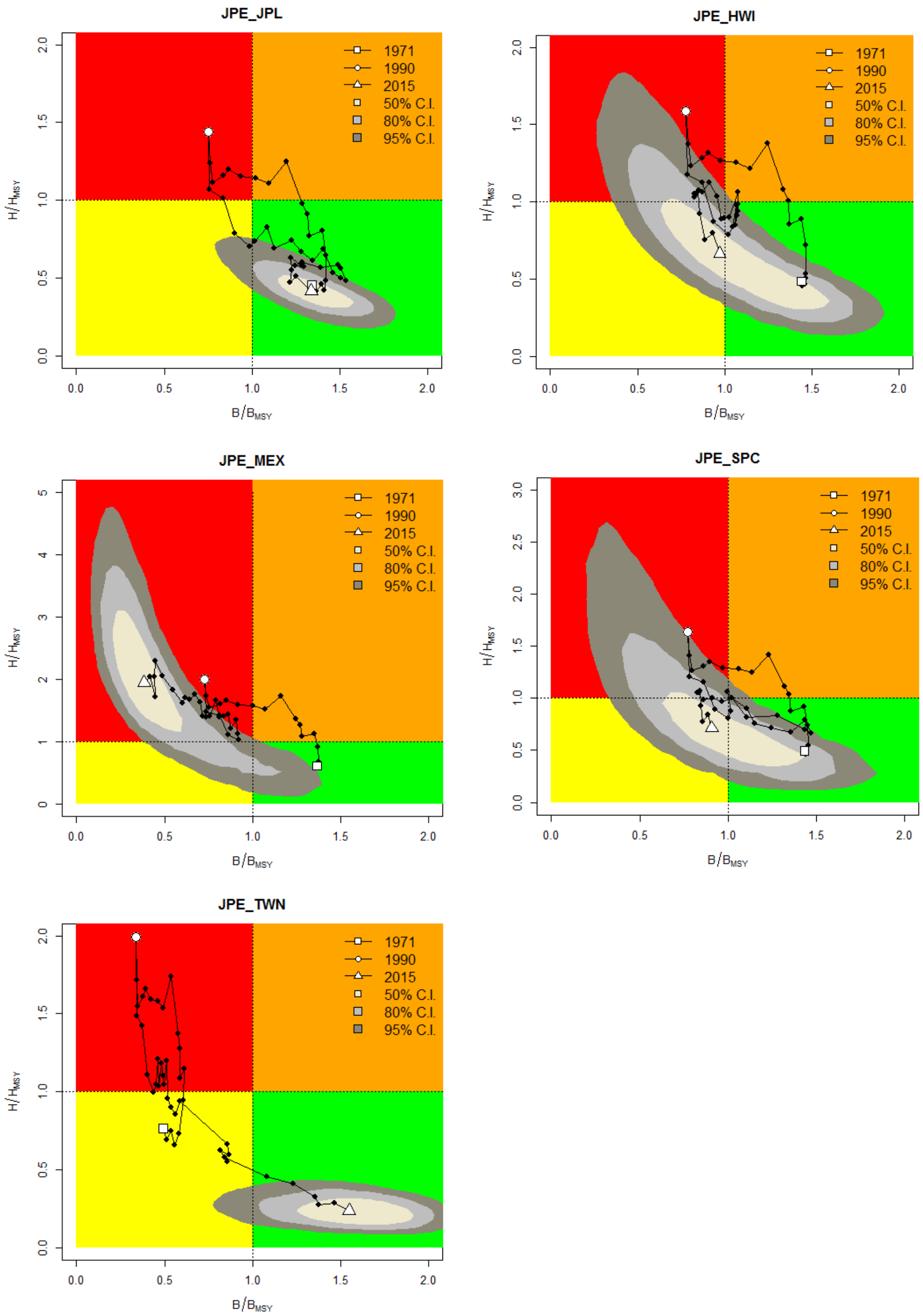

Fig. 7 Kobe plot based on the median trajectories of B/B_{MSY} and H/H_{MSY} for **base-parameter model** of 5 reference cases. Note that the values of B_{MSY} and H_{MSY} are fixed to the medians of posterior distributions.

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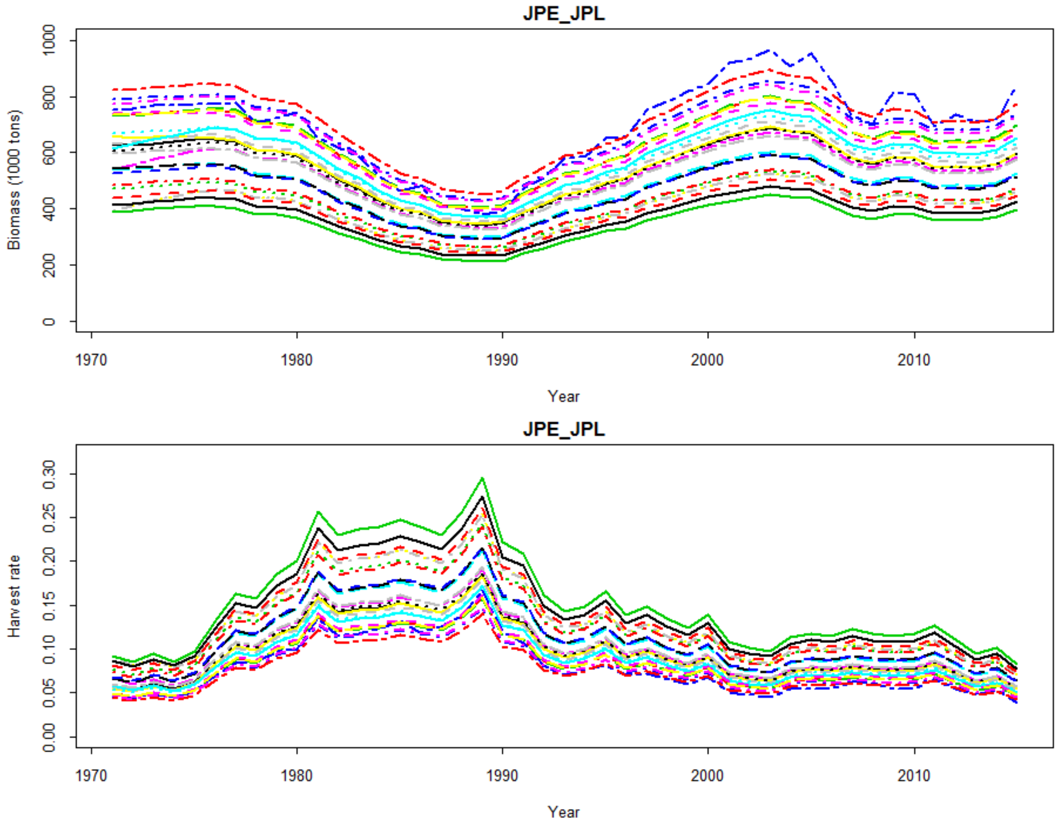

Fig. 8 Comparisons of median estimates for biomass (1000 tons) and harvest rate among different parameterizations (i.e. sensitivity runs) for **JPE_JPL**.

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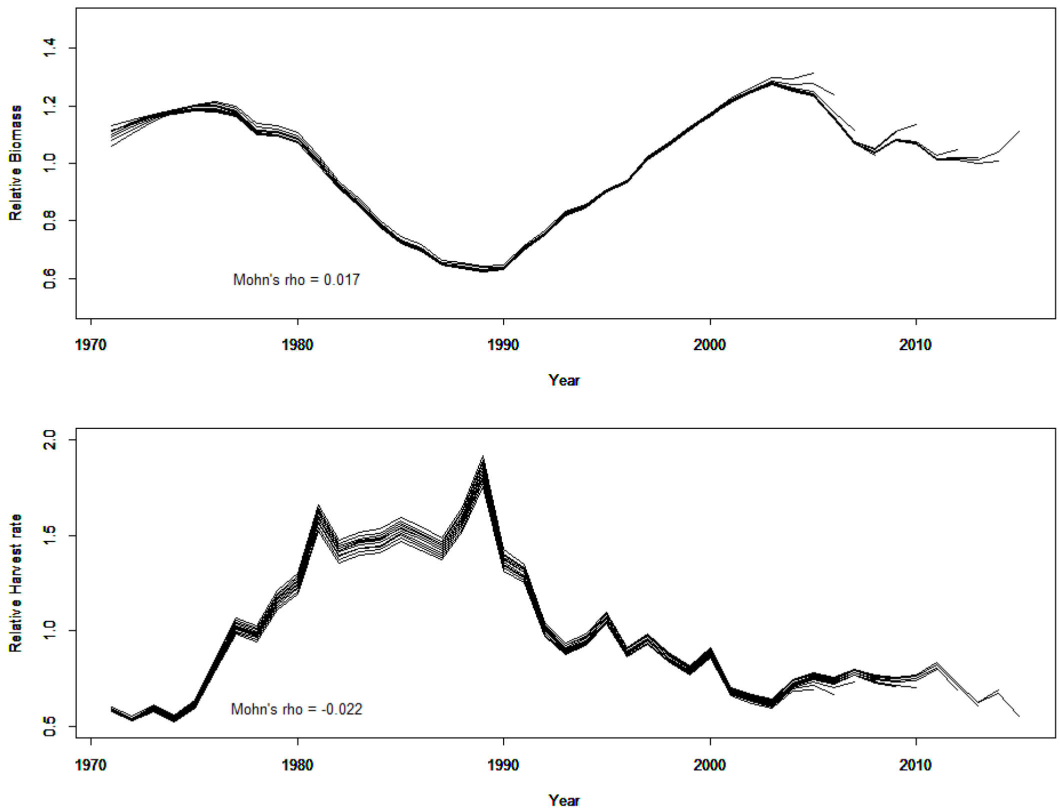

Fig. 9 Historical trajectories of relative biomass to its mean and relative harvest rates from the retrospective analyses of the **base-parameter model** for JPE-JPL.

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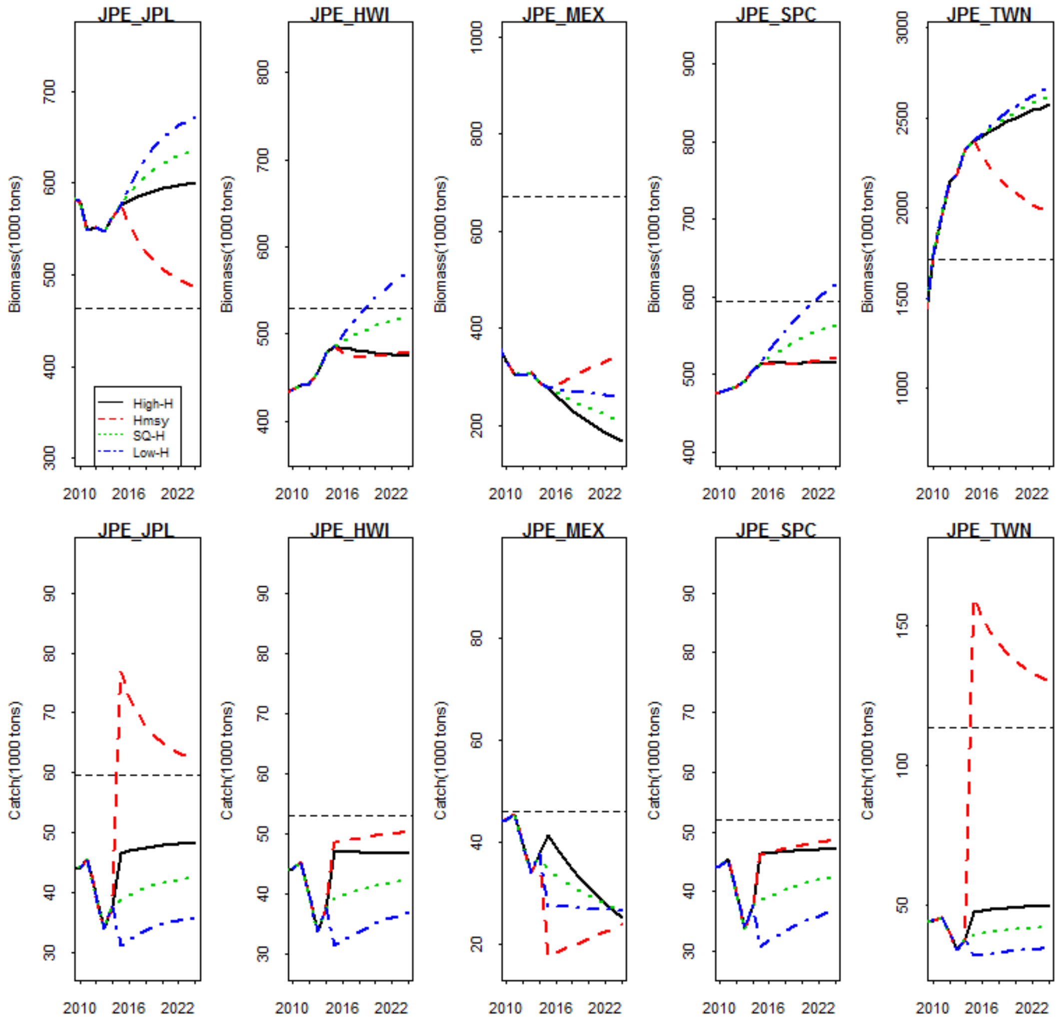

Fig. 10 Historical and projected trajectories of biomass (1000 tons) and catch (1000 tons) for 4 harvest strategies (High-*F*, F_{MSY}, Status-quo, and Low-*F*) from the **base-parameter model** for 5 reference cases. The horizontal dashed line indicates the median estimate for the biomass and Catch at the maximum sustainable yield (B_{MSY} and MSY).

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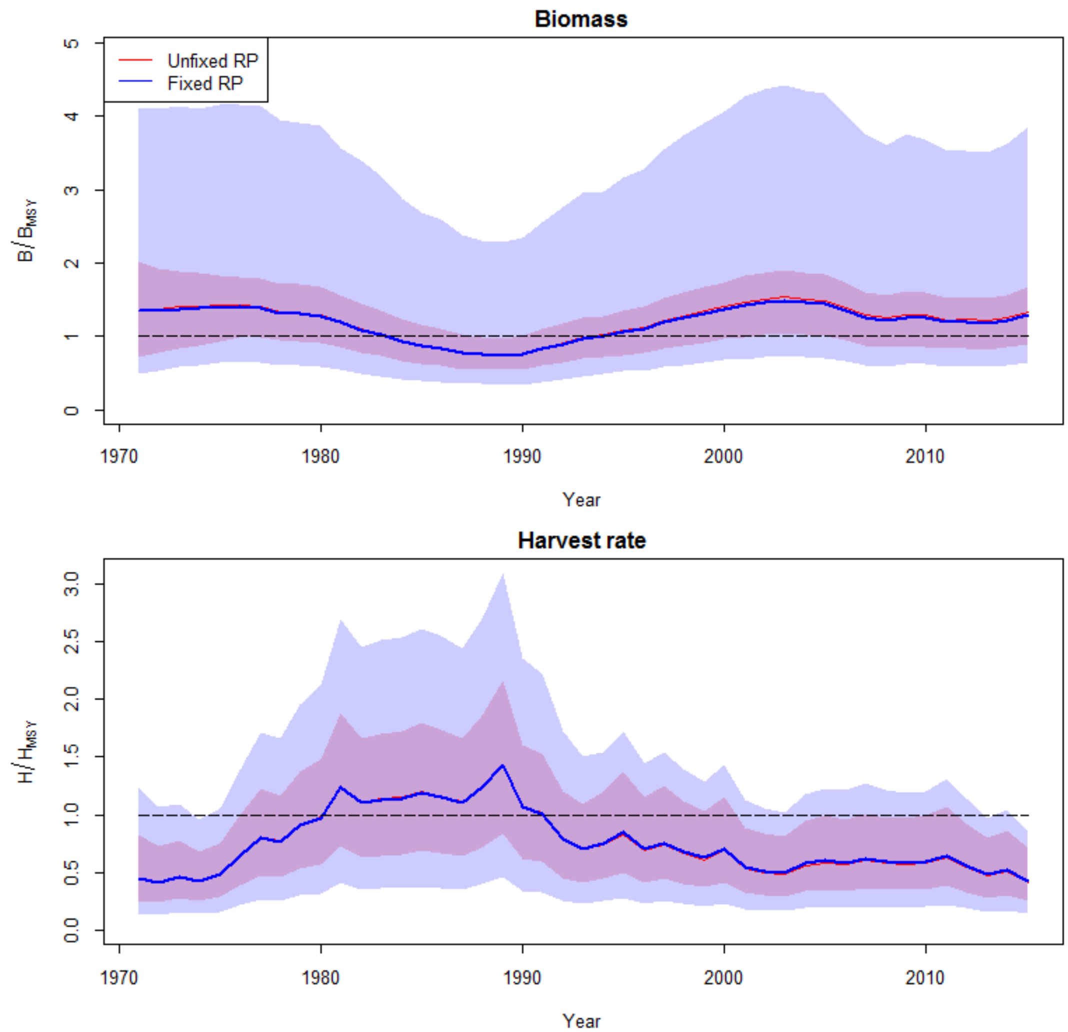

Fig. 11 Comparisons of the historical trajectories of median estimate based on **base-parameter model** and the 95% credible intervals (shadow) for JPE-JPL. The horizontal dashed line indicates the median estimate for the biomass and harvest rate at the reference points (RP: B_{MSY} and H_{MSY}).

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Table A1 Summary table of diagnostics for **base-parameter model** and **best-parameter model** for 10 reference cases. “Rhat” denotes potential scale reduction factor and the value smaller than 1.1 indicates a statistically convergence. “Geweke” denotes the statistical test and the value smaller than 2.042 indicates a statistically convergence.

Fleet	Rhat		Geweke	
	Base-parameter model	Best-parameter model	Base-parameter model	Best-parameter model
JPE-JPL	1.018	2.052	1.003	1.932
JPE-HWI	1.015	1.185	1.003	1.039
JPE-MEX	1.012	1.073	1.010	1.587
JPE-SPC	1.007	0.796	1.005	1.369
JPE-TWN	1.007	1.090	1.006	1.163
JPL	1.045	1.888	1.008	0.736
HWI	1.004	0.842	1.002	1.442
MEX	1.035	1.088	1.007	1.776
SPC	1.007	1.773	1.003	0.589
TWN	1.005	0.452	1.002	3.211

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Table A2. Productivity for base-parameter and sensitivity analyses for different natural mortality schedules. Grey indicates base-parameter.

Scenario	Tmax Male	Female	Reproductive cycle 1year	2year	Mortality estimator	Productivity
1	24	24	Yes		Walter et al. (2016)	0.211
2	24	24		Yes	Walter et al. (2016)	0.173
3	24	19	Yes		Walter et al. (2016)	0.221
4	24	19		Yes	Walter et al. (2016)	0.187
5	19	16	Yes		Walter et al. (2016)	0.247
6	19	16		Yes	Walter et al. (2016)	0.211
7	24	19	Yes		Peterson and Wroblewski (1984)	0.430
8	24	19		Yes	Peterson and Wroblewski (1984)	0.390

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Table A3. Summary of diagnostics on the goodness of fits for CPUE from 10 reference cases of **base-parameter model**. N is total number of time series, RMSE is a root-mean-square-error, and SDNR is a standard deviation of the normalized residuals. An SDNR value greater than the chi-squared statistic (X^2) indicates a statistically poor fit.

Statistics	Combinations of CPUE time series									
	JPE-JPL	JPE-HWI	JPE-MEX	JPE-SPC	JPE-TWN	JPL	HWI	MEX	SPC	TWN
N	18	18	18	18	18					
RMSE	0.064055	0.064262	0.067811	0.06567	0.066834					
SDNR	0.971825	0.971825	0.971825	0.971825	0.971825					
X^2	1.27388	1.27388	1.27388	1.27388	1.27388					
N	22	16	10	17	12	22	16	10	17	12
RMSE	0.065658	0.271559	0.173194	0.201914	0.295883	0.068049	0.343992	0.172953	0.204879	0.295842
SDNR	0.977008	0.968246	0.948683	0.970143	0.957427	0.977008	0.968246	0.948683	0.970143	0.957427
X^2	1.247294	1.290886	1.37109	1.281996	1.337404	1.2473	1.2909	1.3711	1.2820	1.3374

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Table A4. Projected trajectory of biomass (1000 tons) and catch (1000 tons) based on **base-parameter model** under alternative harvest scenarios for 5 reference cases. Green blocks indicate the projection is greater than MSY level (see table 4).

A) Biomass (tons)

Fleet	Harvest scenario	Biomass (1000 tons)										
		2015	2016	2017	2018	2019	2020	2021	2022	2023	2024	Average
JAL	1: High-H (+ 20%)	2021	2033	2042	2048	2058	2065	2070	2077	2080	2085	2058
	2: H_{MSY}	2021	1924	1838	1766	1701	1633	1574	1515	1462	1401	1684
	3: $H_{2012\text{-}2014}$	2021	2040	2056	2067	2082	2093	2104	2109	2119	2128	2082
	4: Low-H (- 20%)	2021	2048	2070	2086	2105	2120	2134	2143	2160	2170	2106
HWI	1: High-H (+ 20%)	970	976	982	986	992	993	998	1001	1003	1006	991
	2: H_{MSY}	970	951	934	916	903	885	872	860	848	835	897
	3: $H_{2012\text{-}2014}$	970	984	998	1009	1019	1028	1040	1048	1055	1064	1022
	4: Low-H (- 20%)	970	992	1013	1032	1049	1064	1081	1096	1111	1125	1053
MEX	1: High-H (+ 20%)	393	378	363	349	337	325	313	302	292	282	333
	2: H_{MSY}	393	400	408	417	427	437	450	461	475	488	436
	3: $H_{2012\text{-}2014}$	393	385	377	370	364	360	356	353	352	350	366
	4: Low-H (- 20%)	393	391	391	391	393	395	399	404	410	418	398
SPC	1: High-H (+ 20%)	1007	1015	1023	1029	1036	1041	1046	1050	1055	1059	1036
	2: H_{MSY}	1007	987	967	947	932	918	900	886	869	852	926
	3: $H_{2012\text{-}2014}$	1007	1022	1038	1051	1064	1074	1084	1096	1106	1114	1066
	4: Low-H (- 20%)	1007	1030	1053	1072	1090	1108	1124	1139	1154	1169	1094
TWN	1: High-H (+ 20%)	1697	1696	1696	1700	1704	1711	1714	1717	1719	1721	1707
	2: H_{MSY}	1697	1621	1560	1505	1454	1404	1355	1313	1268	1227	1440
	3: $H_{2012\text{-}2014}$	1697	1704	1710	1721	1732	1740	1749	1754	1763	1766	1734
	4: Low-H (- 20%)	1697	1711	1723	1742	1759	1773	1783	1795	1805	1811	1760

B) Catch(tons)

Fleet	Harvest scenario	Catch (1000 tons)										
		2015	2016	2017	2018	2019	2020	2021	2022	2023	2024	Average
JAL	1: High-H (+ 20%)	45.9	46.4	46.8	47.2	47.5	47.8	48.0	48.2	48.4	48.5	47
	2: H_{MSY}	137.8	131.5	126.6	122.9	119.7	116.7	114.5	112.6	111.1	109.9	120
	3: $H_{2012\text{-}2014}$	38.2	38.8	39.3	39.8	40.2	40.5	40.8	41.0	41.3	41.5	40
	4: Low-H (- 20%)	30.6	31.2	31.7	32.2	32.6	32.9	33.2	33.5	33.7	33.9	33
HWI	1: High-H (+ 20%)	45.9	46.4	46.8	47.2	47.5	47.8	48.0	48.2	48.4	48.5	47
	2: H_{MSY}	137.8	131.5	126.6	122.9	119.7	116.7	114.5	112.6	111.1	109.9	120
	3: $H_{2012\text{-}2014}$	38.2	38.8	39.3	39.8	40.2	40.5	40.8	41.0	41.3	41.5	40
	4: Low-H (- 20%)	30.6	31.2	31.7	32.2	32.6	32.9	33.2	33.5	33.7	33.9	33
MEX	1: High-H (+ 20%)	41.9	40.1	38.3	36.7	35.2	33.8	32.4	31.1	29.8	28.7	35
	2: H_{MSY}	18.4	19.0	19.6	20.2	20.8	21.4	22.0	22.7	23.3	23.9	21
	3: $H_{2012\text{-}2014}$	34.9	34.1	33.3	32.5	31.8	31.1	30.4	29.8	29.1	28.5	32
	4: Low-H (- 20%)	27.9	27.9	27.8	27.7	27.6	27.6	27.5	27.5	27.4	27.3	28
SPC	1: High-H (+ 20%)	45.8	46.2	46.5	46.8	47.0	47.3	47.5	47.7	47.8	47.9	47
	2: H_{MSY}	59.2	59.0	58.8	58.5	58.3	58.0	57.9	57.7	57.5	57.4	58
	3: $H_{2012\text{-}2014}$	38.2	38.8	39.3	39.8	40.2	40.6	41.0	41.3	41.6	41.9	40
	4: Low-H (- 20%)	30.5	31.3	31.9	32.5	33.0	33.5	33.9	34.4	34.7	35.1	33
TWN	1: High-H (+ 20%)	47.4	47.8	48.1	48.4	48.7	48.9	49.1	49.3	49.5	49.6	49
	2: H_{MSY}	159.9	153.0	147.7	143.7	140.3	137.3	135.3	133.2	131.6	130.0	141
	3: $H_{2012\text{-}2014}$	39.5	39.9	40.4	40.7	41.0	41.3	41.5	41.7	41.9	42.1	41
	4: Low-H (- 20%)	31.6	32.1	32.5	32.9	33.2	33.5	33.7	33.9	34.1	34.3	33

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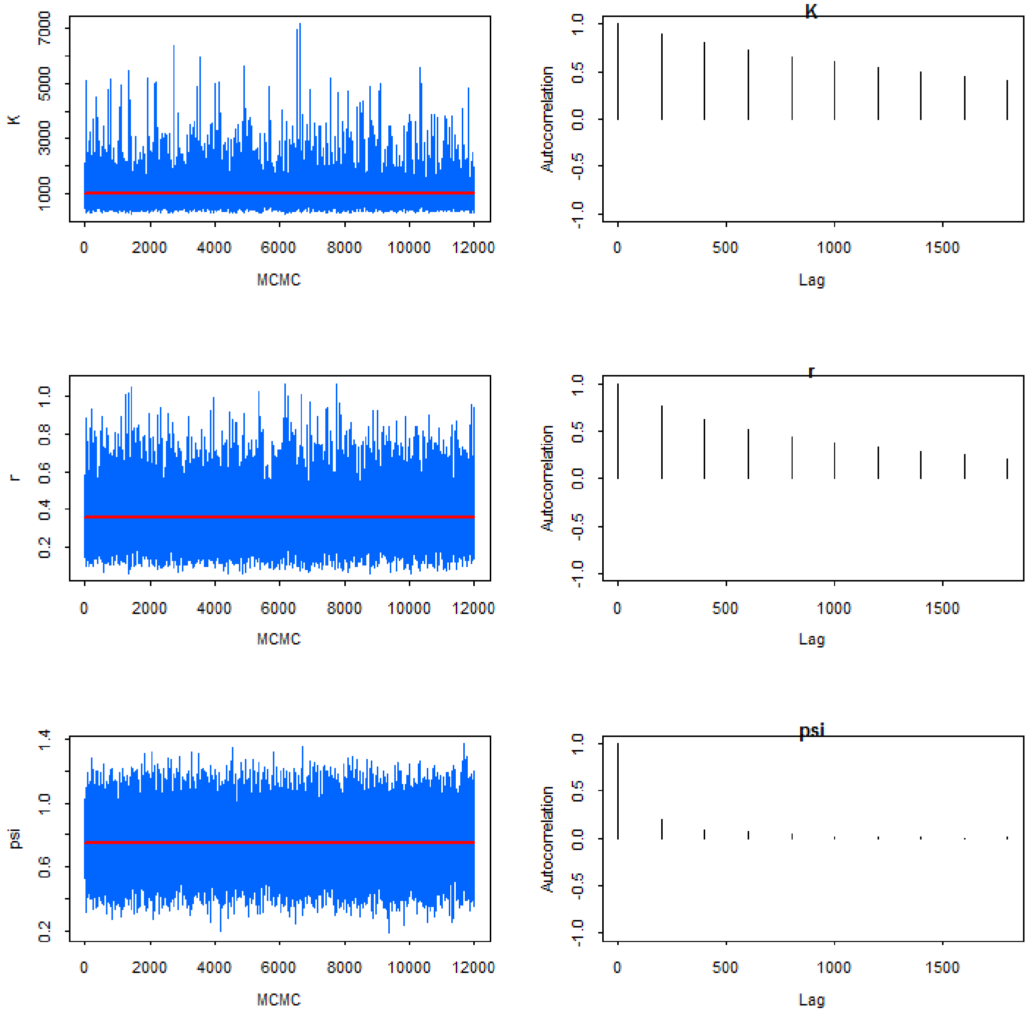

Fig. A1. An example of the trace of the MCMC samples (4000 x 3 chains) and the auto correlations for the key parameters (K, r and $\varphi(= B_{1971}/K)$) of **base parameter model**.

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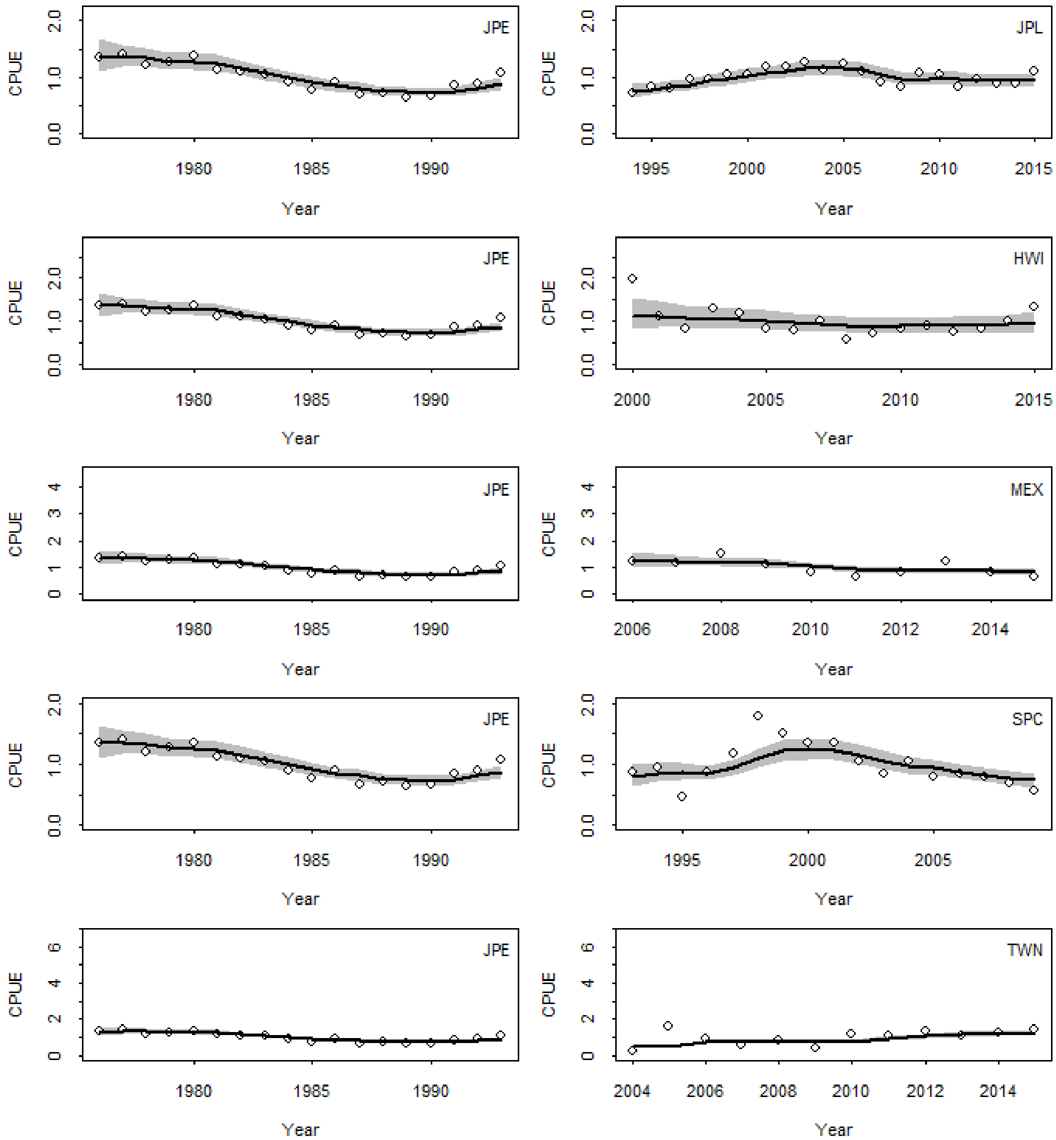

Fig. A2.1 Yearly changes in predicted CPUE (thick line) with 95% credible intervals (grey shadow) and observed CPUE (open circle) for 5 reference cases (**JPE_JPL, JPE_HWI, JPE_MEX, JPE_SPC, JPE_TWN**).

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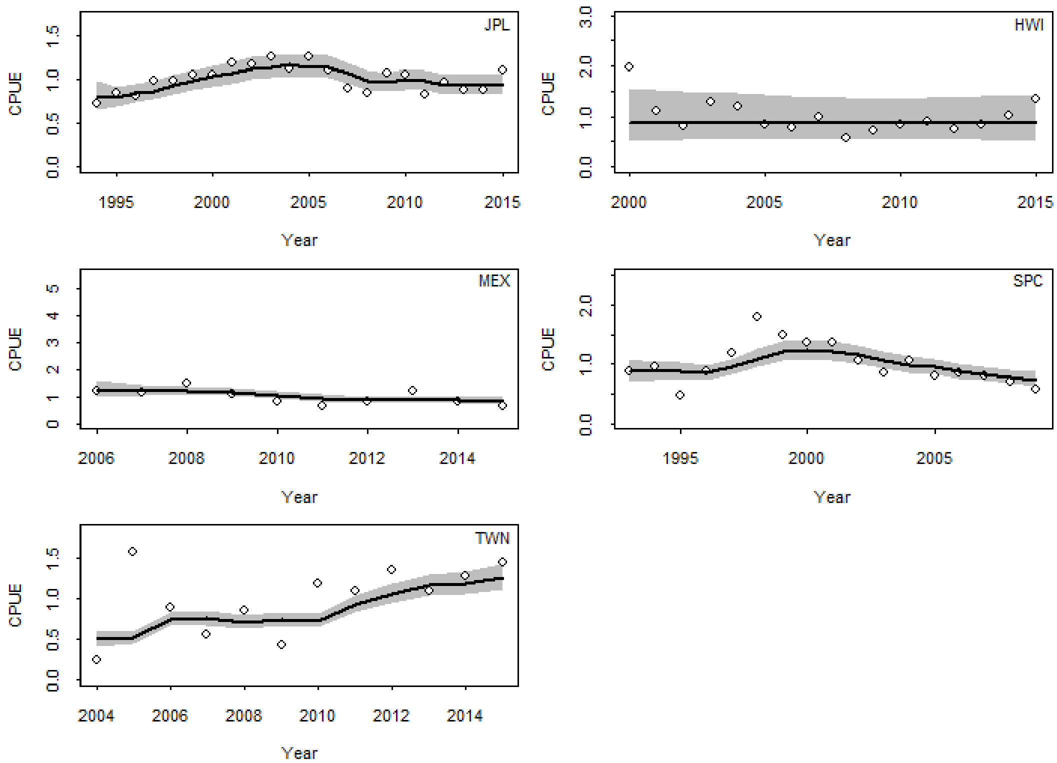

Fig. A2.1 Yearly changes in predicted CPUE (thick line) with 95% credible intervals (grey shadow) and observed CPUE (open circle) for 5 reference cases (**JPL, HWI, MEX, SPC, TWN**).

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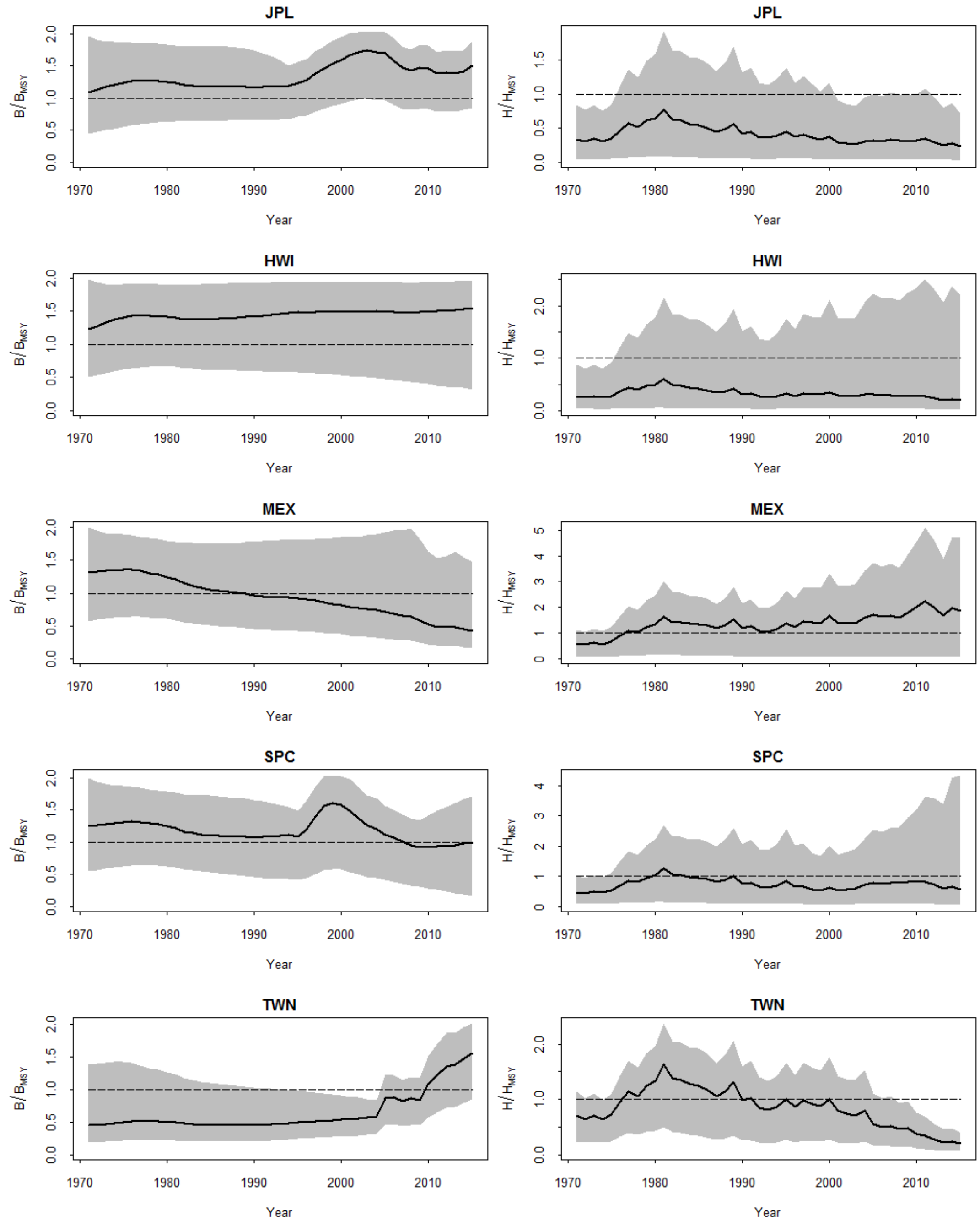

Fig. A3 Historical trajectories of median estimate of relative harvest rate and biomass based on **base-parameter model** and the 95% credible intervals (grey shadow) for 5 reference cases. The horizontal dashed line indicates the median estimate for the biomass and harvest rate at the maximum sustainable yield (B_{MSY} and H_{MSY}).

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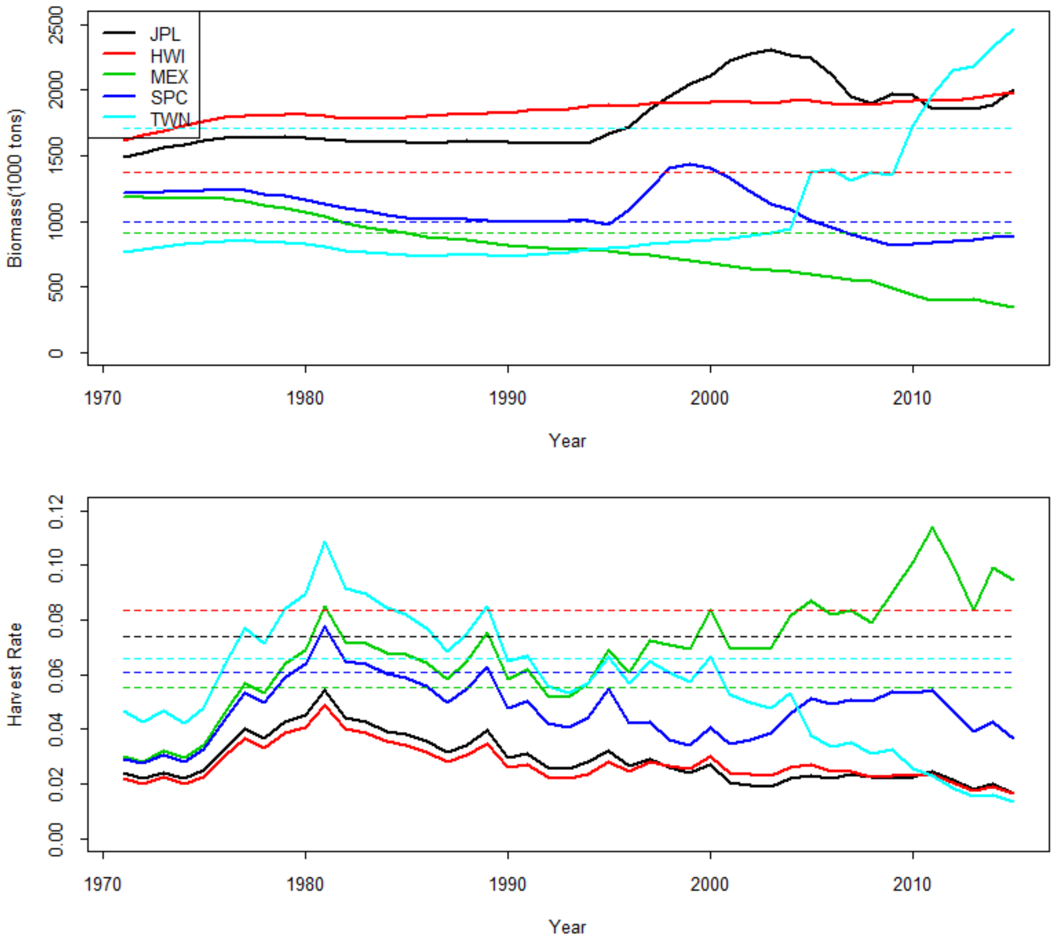

Fig. A4 Historical trajectories of median estimates based on **base-parameter model** for biomass (1000 tons) and harvest rate among 5 reference cases. The horizontal dashed line indicates the median estimate for the biomass and harvest rate at the maximum sustainable yield (B_{MSY} and H_{MSY}).

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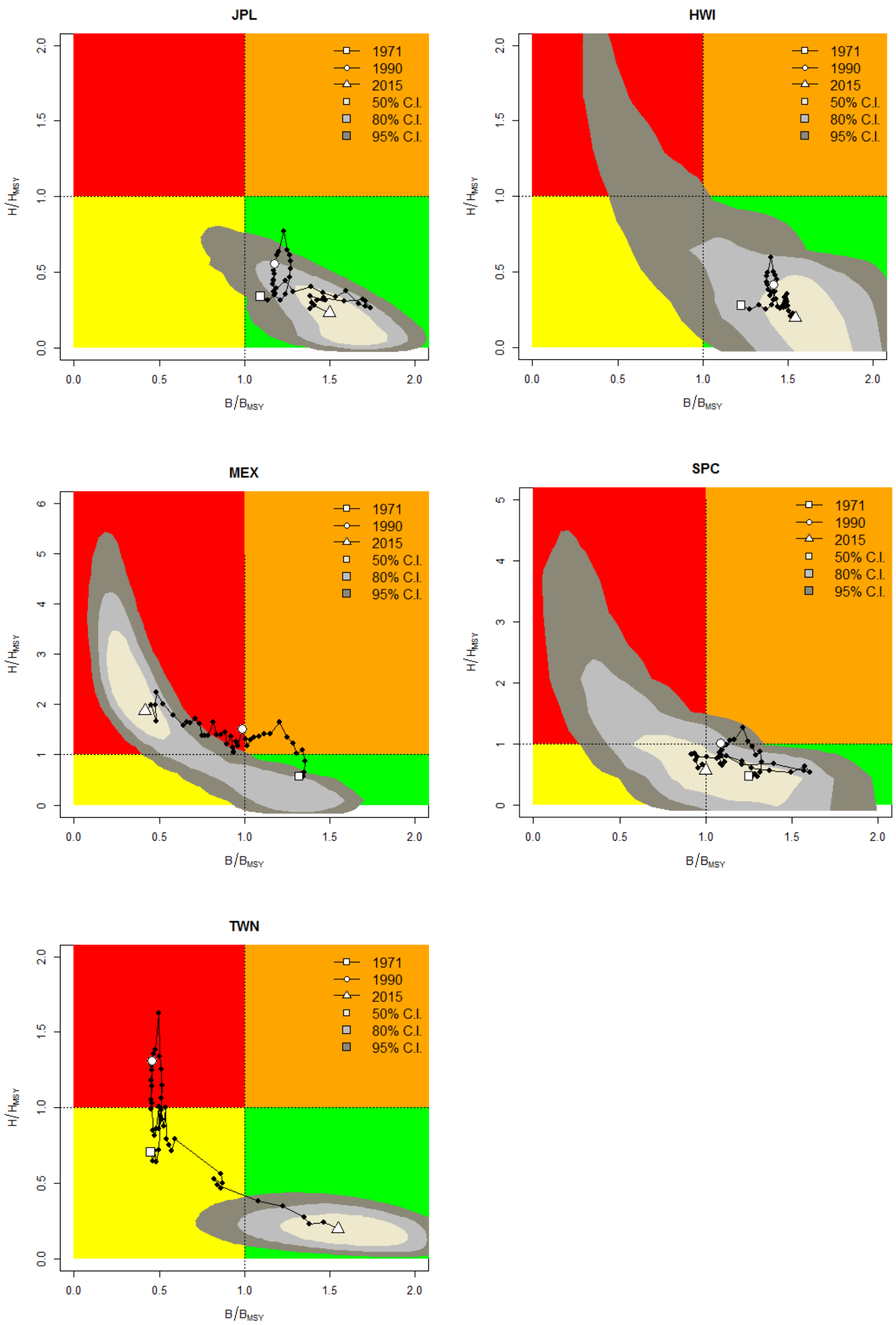

Fig. A5 Kobe plot based on the median trajectories of B/B_{MSY} and H/H_{MSY} for **base-parameter model** from 5 reference cases.

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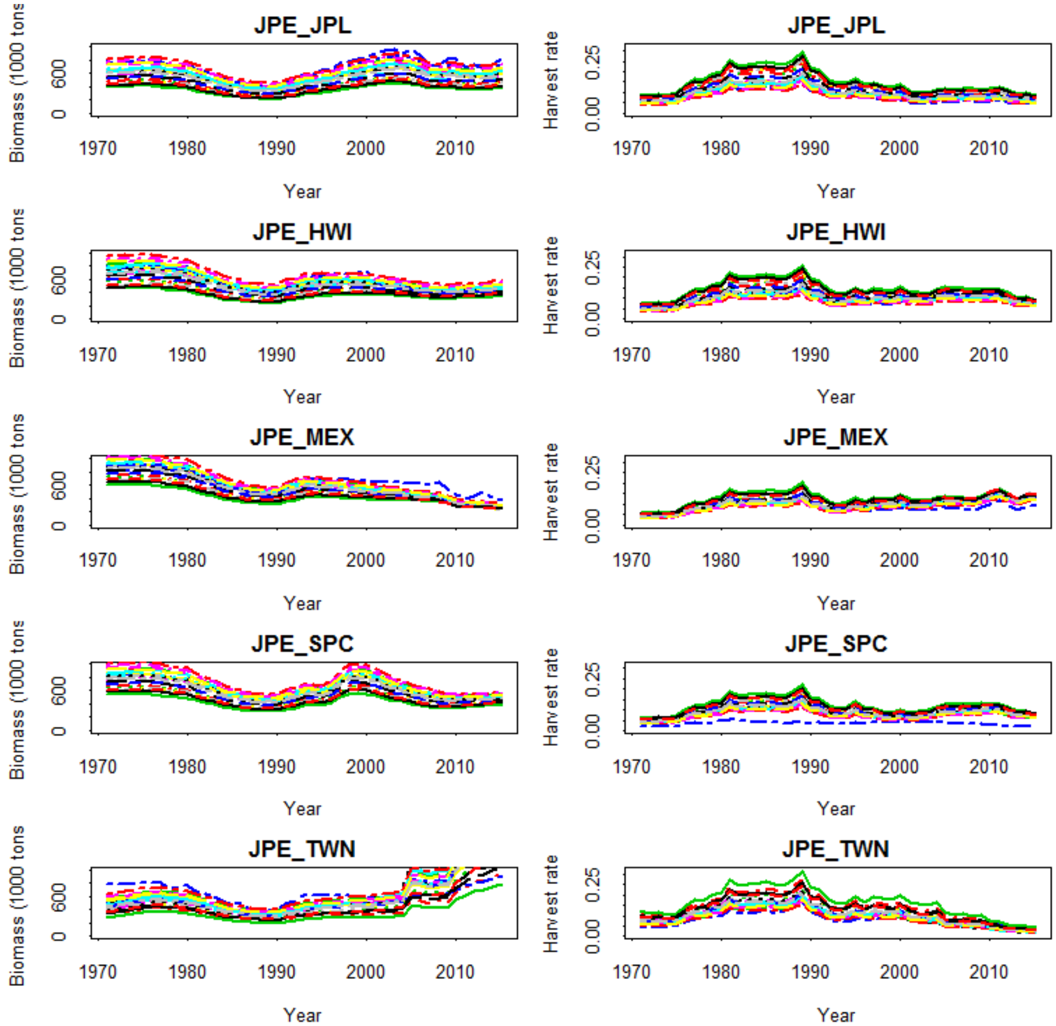

Fig. A6.1 Comparisons of median estimates for biomass (1000 tons) and harvest rate among different parameterizations (i.e. sensitivity runs) for 5 reference cases (**JPE_JPL**, **JPE_HWI**, **JPE_MEX**, **JPE_SPC**, **JPE_TWN**). See Fig. 8 w.r.t. legends of each lines.

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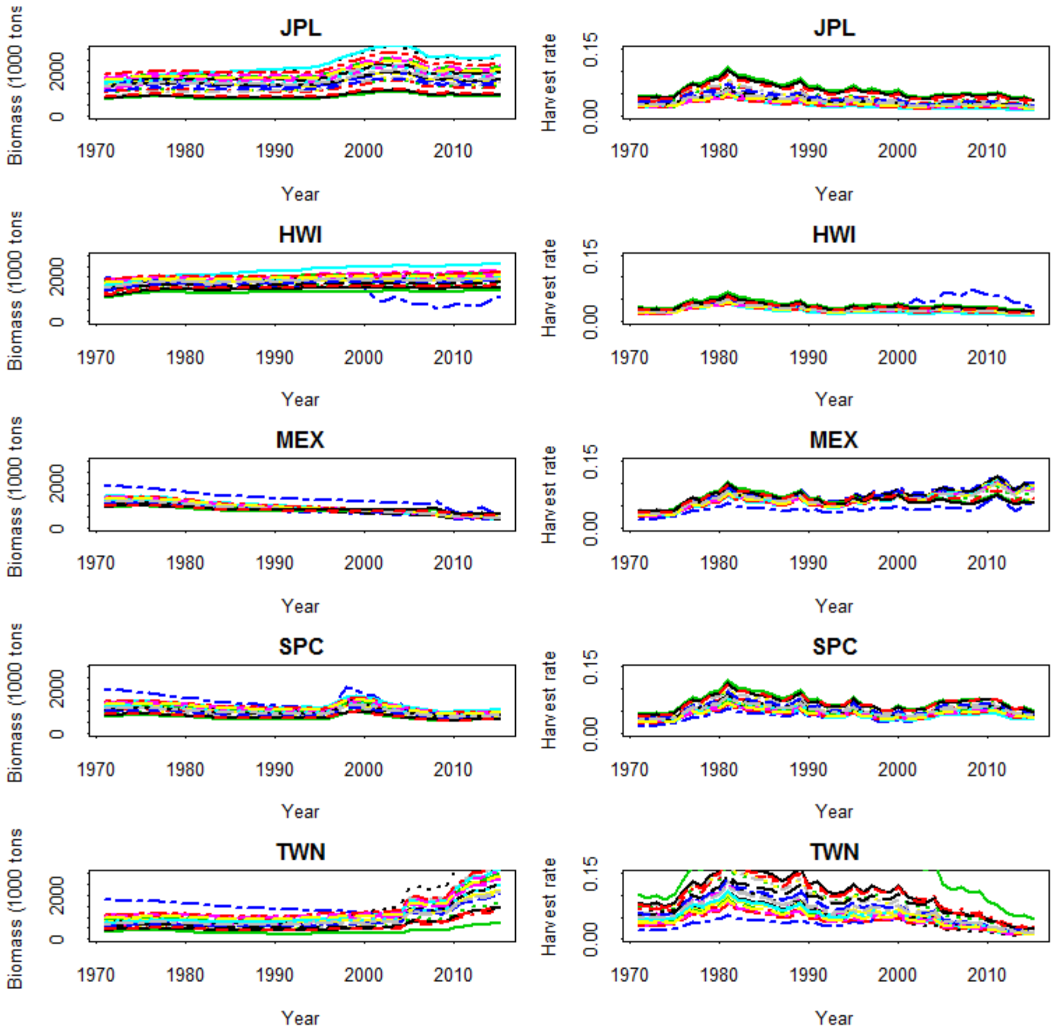

Fig. A6.2 Comparisons of median estimates for biomass (1000 tons) and harvest rate among different parameterizations (i.e. sensitivity runs) for 5 reference cases (**JPL**, **HWI**, **MEX**, **SPC**, **TWN**). See Fig. 8 w.r.t. legends of each lines.

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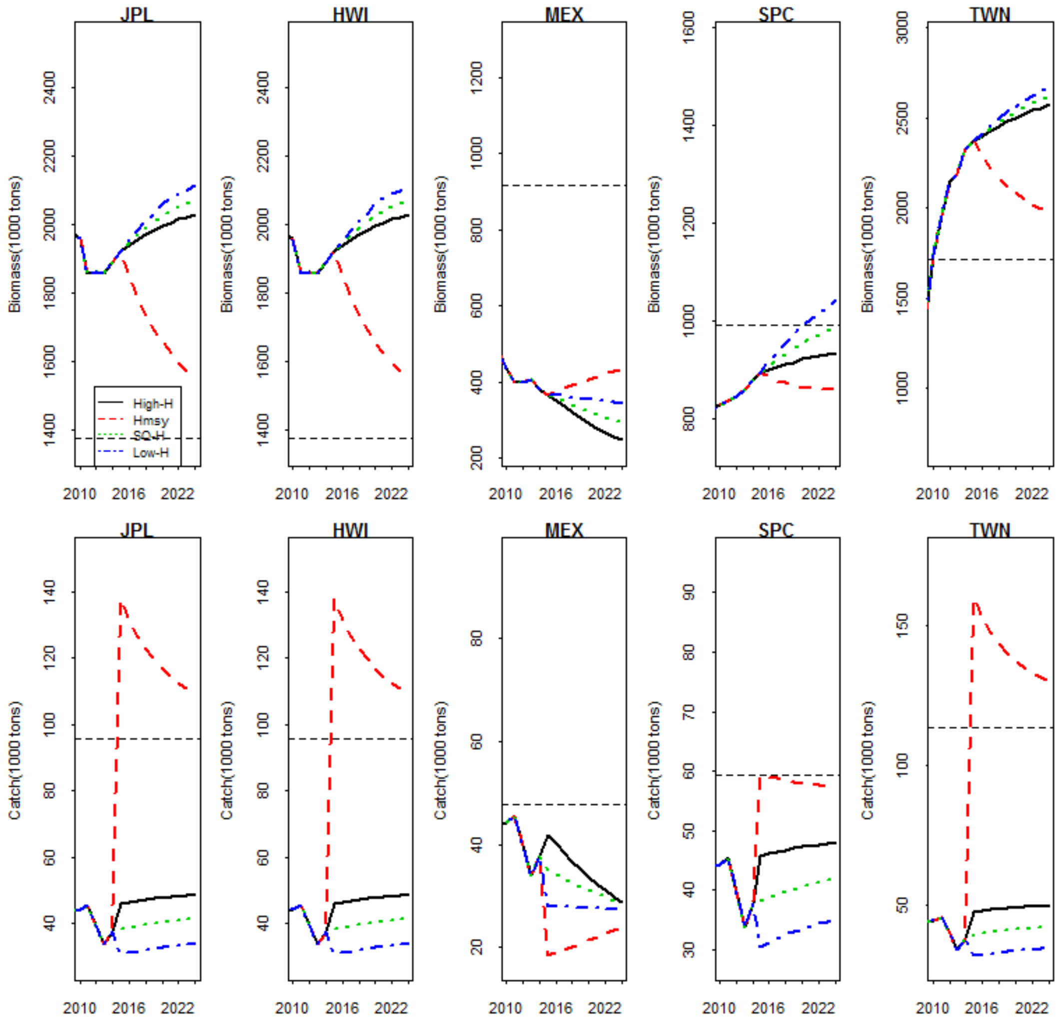

Fig. A7 Historical and projected trajectories of biomass (1000 tons) and catch (1000 tons) for 4 harvest strategies (High-*H*, H_{MSY}, Status-quo ($H_{2012\text{-}2014}$), and Low-*H*) from the **base-parameter model** for 5 reference cases. The horizontal dashed line indicates the median estimate for the biomass and Catch at the maximum sustainable yield (B_{MSY} and MSY).

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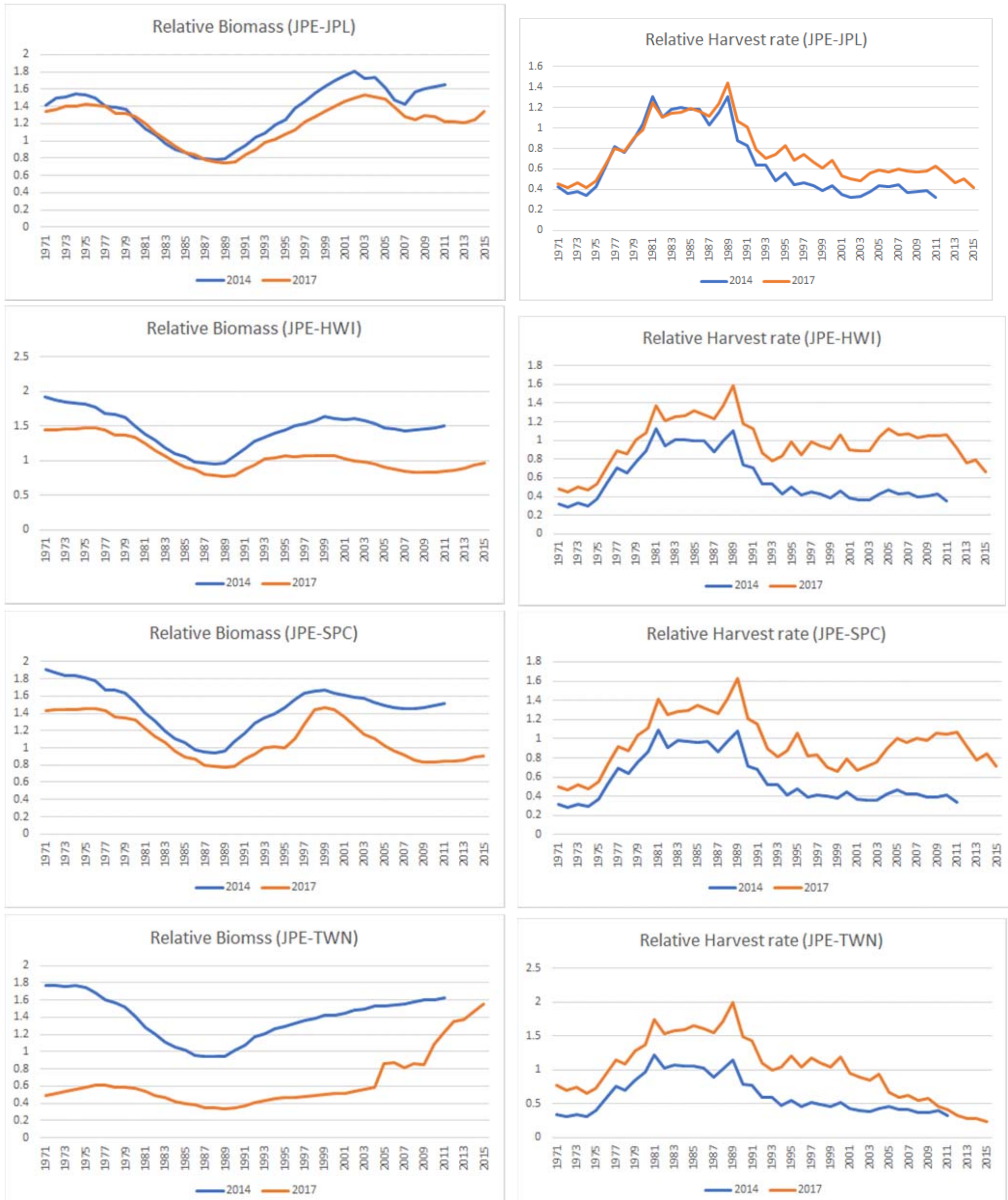

Fig. A8 Comparisons of the relative biomass and harvest rate to MSY-based reference points (B_{MSY} and H_{MSY}) between previous (2014) and current (2017) stock assessment results for 4 reference cases.

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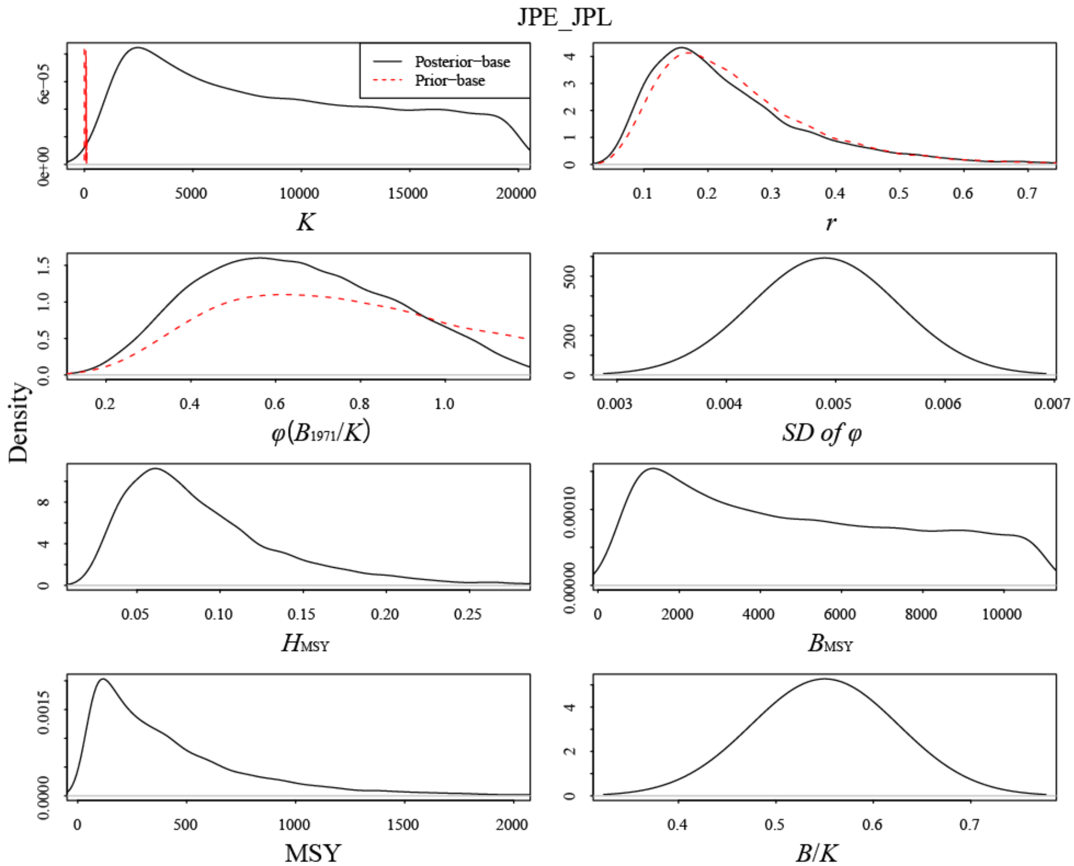

Fig. A9 Marginal posterior distributions (solid line) of key parameters (K, r,) and variables (φ=B_{1971}/K:psi, SD of φ, H_{MSY}, B_{MSY}, MSY, B_{MSY}/K) for **Prior only run**. Dotted line indicates the prior distributions. Black and red lines denote the prior and posterior distributions of base-parameters and best-parameters respectively.

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