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Impacts of misspecification of spawner-recruitment relationship on stock assessment: An example of South Pacific albacore tuna

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Wang J[1,3], X. Chen[1,2], J. Zhua[1,2], J. Cao[3] and Y. Chen[1,3]

[1] College of Marine Sciences, Shanghai Ocean University, Shanghai 201306, China
[2] Key Laboratory of Sustainable Exploitation of Oceanic Fisheries Resources, Ministry of Education, Shanghai Ocean University, Shanghai 201306, China
[3] School of Marine Sciences, University of Maine, Orono, ME 04469, USA

Impacts of misspecification of spawner-recruitment relationship on stock assessment: An example of South Pacific albacore tuna

Jintao Wang[a,c], Xinjun Chen[a,b], Jiangfeng Zhu[a,b], Jie Cao[c], Yong Chen[a,c]

a College of Marine Sciences, Shanghai Ocean University, Shanghai 201306, China;

b Key Laboratory of Sustainable Exploitation of Oceanic Fisheries Resources, Ministry of Education, Shanghai Ocean University, Shanghai 201306, China;

c School of Marine Sciences, University of Maine, Orono, ME 04469, USA

Abstract

Identifying spawner-recruitment relationship is critically important to contemporary fishery stock assessment and management. In this study, the impacts of misspecification of spawner-recruitment relationship on fisheries stock assessment and management were evaluated, using South Pacific albacore tuna (*Thunnus alalunga*) as an example. The estimates of maximum sustainable yield (MSY) and MSY-based reference points are sensitive to the value of standard deviation of log recruitment (σ_R) (ranging from 0.2 to 1.0) of the Beverton-Holt (B-H) and Ricker spawner-recruitment (S-R) relationships. The steepness of those two S-R relationships was estimated reasonably. The σ_R can also impact the evaluation of stock status. Simulation analyses show that in most cases mis-specifying B-H S-R relationship to Ricker S-R relationship or mis-specifying Ricker S-R relationship to B-H S-R relationship resulted in more optimistic evaluations of stock status. This study stresses that spawner-recruitment relationship should be more carefully defined when management is based on MSY-based reference points.

1 Introduction

The relationship between spawners and recruitment (S-R relationship) is one of the most uncertain process of fish population dynamics and is highly influential to fisheries management advice (Method and Taylor, 2011; Maunder, 2012). This is caused by several of reasons including error in estimating biomass and recruitment, process variability, lack of estimates of recruitment at low spawning stock size (Hilborn and Walters, 1992; Quinn and Deriso, 1999).

The Beverton-Holt (B-H) curve and Ricker curve are most often used to model S-R relationship. For integrated stock assessment modelling, such as Stock Synthesis, these two curves are re-parameterized by two parameters, the average virgin recruitment (R_0) and the steepness (h) (Maunder and Watters, 2003; Methot, 2005). Recent attempts to estimate and interpret B-H S-R relationship were problematic and the resulted management reference points and stock status were less reliable. In most cases, steepness of B-H S-R relationship was estimated with moderate to low precision and moderate to high bias (Lee et al., 2012). Meanwhile, Maunder (2012) indicated that the steepness of B-H S-R relationship is difficult to estimate and a lower value of steepness might be appropriate for summer flounder in the U.S. mid-Atlantic Ocean using simulation analysis. The impacts of steepness parameter of the B-H S-R relationship curve on fisheries stock assessment have been evaluated using data for bigeye tuna in the eastern Pacific Ocean (Zhu et al., 2012). The maximum sustainable yield (MSY), MSY related management reference points, and evaluations of stock status are sensitive to the value of steepness (Zhu et al., 2012).

Variability in recruitment for fisheries stock assessment models is typically modeled using a lognormal distribution and it is represented by σ_R in Stock Synthesis (Methot and Taylor, 2011). This parameter has two roles. It penalizes deviations from the S-R curve and defines the offset between the arithmetic mean S-R curve and the expected geometric mean (Methot, 2013). This value must be selected to approximate the true average recruitment deviation. In application, this quantity is also not known and estimation of σ_R is known to be problematic in fisheries assessment models (Maunder and Deriso, 2003). However, how the σ_R assumption impacts parameter estimation and management reference points in stock assessment was few studied.

Generally, the B-H model is used for marine teleost species and Ricker model is used for salmonids and for species where cannibalism is occurred. In practice, both the form and the estimation of parameters for S-R relationship exhibit uncertainties (Hilborn and Walters, 1992; Magnusson and Hilborn, 2007; Conn et al., 2010). However, most previous studies only focus on the uncertainty associated with parameter estimation.

In this study, we use albacore tuna in the southern Pacific Ocean (SPO) to illustrate the impact of misspecification of both S-R relationship form and recruitment deviation on estimates of reference points and stock status. First, we analyze how the standard deviation of log recruitment (σ_R) impacts parameter estimation, MSY, and MSY-based management reference points for the two S-R relationships (B-H and Ricker models). Then, we evaluate management implication based on MSY-based management reference points if S-R relationship is mis-specified in the assessment model.

2 Methods

2.1 Sensitivity analysis

The albacore tuna model based on Stock Synthesis (Cao et al., 2016) was used to explore the sensitivity of estimates of R_0 and h and management quantities to the value of standard deviation of log recruitment (σ_R). This model includes 14 fisheries (8 longline fisheries, 3 driftnet fisheries and 3 troll fisheries) and uses a quarterly time step from 1960 to 2013. The length-based selectivity curves for 14 fisheries are assumed to be dome-shaped, and the selectivity parameters are estimated when fitting the model except for the two parameters of the double normal curve defining the initial selectivity at first bin and the final selectivity at last bin, which are fixed at low values to avoid numerical estimation issues (Zhu et al., 2015). Other configurations of data set and model structure follow Hoyle et al. (2012).

For the sensitivity analysis, the albacore tuna assessment model was run by fixing parameter σ_R at different values from 0.2 to 1.0 with a step of 0.2 for both B-H and Ricker S-R models. Impacts on the stock assessment were evaluated based on key model outputs relating to management quantities.

2.2 Simulation analysis

Simulation analyses were used to evaluate the impacts of misspecification of S-R relationship on management quantities. The albacore tuna assessment model was used as simulator and estimator to control misspecification associated with S-R relationships. We focus on the impact of misspecification of S-R relationship form, but still considering the impact of recruitment deviation. The simulation steps are as follows:

(1) The parameters in model with B-H S-R relationship estimated in Section 2.1 are used to generate artificial (simulated) data sets based on the characteristics of the data used for fitting the model (catch, indices of relative abundance and length composition by fishery) and sampling distribution assumptions.

(2) The model is then fit to the simulated data by assuming a Ricker S-R relationship. All other parameters (i.e., natural mortality, fecundity, length-weight relationship) were fixed at values used in the simulator.

(3) Steps (1) – (2) are repeated 100 times.

(4) Steps (1) – (3) are repeated for a range of values of σ_R. The same procedure was used for the case of assuming a B-H S-R relationship in the estimators to fit to the data sets generated from a model with Ricker S-R relationship.

2.3 Model fit and derived management reference points

The models in sensitivity analysis and simulation analysis were fitted with different assumptions of σ_R values. In order to avoid the range of parameters affecting the results of stock assessment, wide ranges for parameters R_0 and h values were set and priors were not used. We defined the model convergence when the eigen values of Hessian matrix are positive and the maximum gradients from the minimization procedure are less than 0.1. To determine if the estimation of S-R relationship was the cause of non-convergence of the mis-specified models, all simulated data sets were fit using a model with "true" S-R relationship. If previously non-converged models converged after changing to "true" S-R relationship, then we consider that the estimation of S-R relationship to be cause of the convergence issue. Non-converged model runs were deleted before further analysis.

Assessment of stock status was evaluated based on MSY and related reference points such as SSB_{MSY} (spawning stock biomass corresponding to MSY), F_{MSY} (fishing mortality corresponding to MSY), SPR_{MSY} (spawning potential ration corresponding to MSY), and $B_{current}/B_{MSY}$ (the ration of biomass of the last year to biomass corresponding to MSY). Maximum depletion was defined as follows to characterize the exploitation history under different scenarios:

$$Maximum\ depletion = \min\left(\frac{SSB_t}{SSB_0}\right), t = t_1, t_2, \ldots, t_N$$

The medians of those statistics were used to make general conclusion.

3 Results

3.1 Impacts on parameters and management reference points

A total of 177 parameters were estimated in each run of the model in sensitivity analysis. For B-H S-R curve assumed, there was an improvement in the model fit (total negative log-likelihood improvement of 185.4 units) when the highest σ_R was 1.0, compared with the fit when the lowest σ_R was 0.2; for Ricker S-R curve assumed, the model fit was improved by 409.1 units when σ_R was 0.8, compared with the fit when the σ_R was 0.4 (Fig. 1). All the data components (including CPUE, length composition and recruitment) supported σ_R = 1.0 when B-H curve was assumed, and supported σ_R = 0.8 when Ricker curve was assumed (Fig. 1). The S-R parameters (R_0, h) showed different changing trends along with σ_R. When B-H curve was assumed, the estimates of R_0 and h were more stable; however, R_0 was increasing and h was decreasing with the σ_R changing from 0.2 to 1.0 when Ricker curve was assumed (Fig. 2).

The estimates of MSY and related management reference points were sensitive to the values of standard deviation of log recruitment. With increasing σ_R, the MSY and F_{MSY} increased, whereas the SPR_{MSY} decreased (Fig. 3a, 3c and 3d); the SSB_{MSY} increased for B-H S-R curve, but decreased for Ricker S-R curve (Fig. 3b).

3.2 Impacts on the evaluation of stock status

The assumed standard deviation of log recruitment value impacted the evaluation of stock status of South Pacific albacore tuna. The values of maximum depletion were reduced from 0.50 to 0.41 for B-H S-R relationship and reduced from 0.50 to 0.36 for Ricker S-R relationship respectively, both with the σ_R from 0.2 to 1.0 (Fig. 3f). However, the current stock statuses with different σ_R values were almost the same for B-H and Ricker S-R relationships (Fig. 3e).

3.3 Impacts of misspecification of S-R relationship

The proportions of converged models (Table 1) (R_0 and h estimated) ranged from 0.78 to 0.92 when the B-H S-R relationship was mis-specified as Ricker S-R relationship, and ranged from 0.78 to 0.86 when the Ricker S-R relationship was mis-specified as B-H S-R relationship. Model runs with "true" S-R relationship did not generally improve the proportion of converged models. This indicated that selection bias would not be generated by the discarding the cases with non-converged models in the further analyses.

Management reference points were almost larger and stock statuses were more optimistic in mis-specified models than those in "true" models. When mis-specifying B-H S-R relationship to Ricker S-R relationship, it resulted in increases of MSY (13% at σ_R = 0.2 and 35% at σ_R = 0.8; Fig. 4a), increases of SSB_{MSY} (7% at σ_R = 0.2 and 10% at σ_R = 0.6; Fig. 4b), decreases of SPR_{MSY} (1% at σ_R = 0.2 and 11% at σ_R = 0.8; Fig. 4d), and a slightly more F_{MSY}, $B_{current}/B_{MSY}$ and Maximum depletion (Fig 4c, 4e and 4f). When mis-specifying Ricker S-R relationship to B-H S-R relationship, Fig. 5 showed increases of MSY (15% at σ_R = 0.2 and 50% at σ_R = 0.6; Fig. 5a), increases of F_{MSY} (30% at σ_R = 0.8 and 72% at σ_R = 1.0; Fig. 5c), increases of $B_{current}/B_{MSY}$ (9% at σ_R = 0.2 and 72% at σ_R = 1.0; Fig. 5e), increases of Maximum depletion (1% at σ_R = 0.4 and 8% at σ_R = 1.0) except for σ_R = 0.2 (Fig. 5f), decreases of SPR_{MSY} (10% at σ_R = 0.2 and 36% at σ_R = 0.8; Fig. 4d), and decreases of SSB_{MSY} (3% at σ_R = 1.0 and 31% at σ_R = 0.6; Fig. 4d).

4 Discussions

Though likelihood-related hypothesis test based on stock assessment models is generally unreliable (Zhu et al., 2012), the negative log-likelihood values for B-H and Ricker S-R relationships in this study were highly statistically significant when different σ_R values were assumed. In many cases, steepness is not estimated, but fixed or borrowed from other stocks or species (Myers et al., 1999, 2002; Dorn 2002) or based on life history theory (He et al, 2006; Mangel et al., 2010). For the purpose of the study, the steepness for the B-H and Ricker curves were all estimated. The steepness for B-H S-R relationship was estimated to be from 0.63 to 0.78 when σ_R was assumed from 0.2 to 1.0, which agrees with lift history theory and the steepness values assumed in recent stock assessment for albacore tuna in SPO (Harley et al., 2015; Cao et al., 2016).

The assessment results for albacore tuna in SPO are similar to those from the MULTIFAN-CL (Harley et al., 2015). The recent SSB is either at or less than SSB_{MSY}, and recent levels of fishing mortality are little higher than the level that will support MSY (Fig. 6). It suggests that fishing mortality should not be further increased to avoid the decline of albacore tuna stock in SPO.

An intermediate and common-taken path for selecting S-R relationship is to base the choice of the shape of the curve on assumed biology, and to use statistical methods to estimate the parameters of the selected model. No any strict criteria for selecting the appropriate model for a stock has been developed (Needle, 2002). In this study, the mis-specified S-R relationship did not lead to more convergence issues than the “true” S-R relationship. This might indicate that the S-R relationship of a fish population is obscured by various factors and it is very difficult to identify. It should be noted that our conclusion in this study was derived from specific fisheries and stock. More work represents a broad scope of life histories and fishery dynamics should be conducted to obtain a more general conclusion about the implication of misspecification of S-R relationship for fishery management. Nevertheless, we suggest that considering the impact of misspecification of S-R relationship on fisheries management should be the top priority.

Acknowledgements

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Tables

Table 1 Specification of scenarios for simulation analysis

S-R cruve	B-H		Ricker	
σ_R	"True"	Mis-specified	"True"	Mis-specified
0.2	0.80	0.78	0.79	0.78
0.4	0.86	0.88	0.78	0.79
0.6	0.91	0.90	0.85	0.82
0.8	0.94	0.92	0.88	0.86
1.0	0.82	0.80	0.78	0.80

Figures

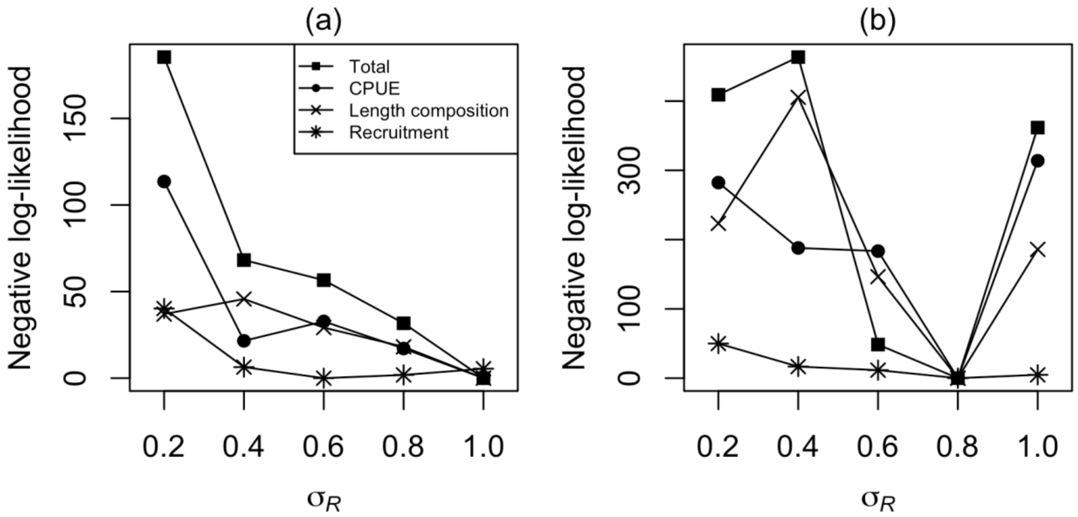

Figure 1 Likelihood profile on the standard deviation of log recruitment in the SS3 model for albacore tuna in the South Pacific Ocean. The negative log-likelihood values were rescaled by subtracting the lowest value for each data type, (a) for B-H curve, (b) for Ricker curve.

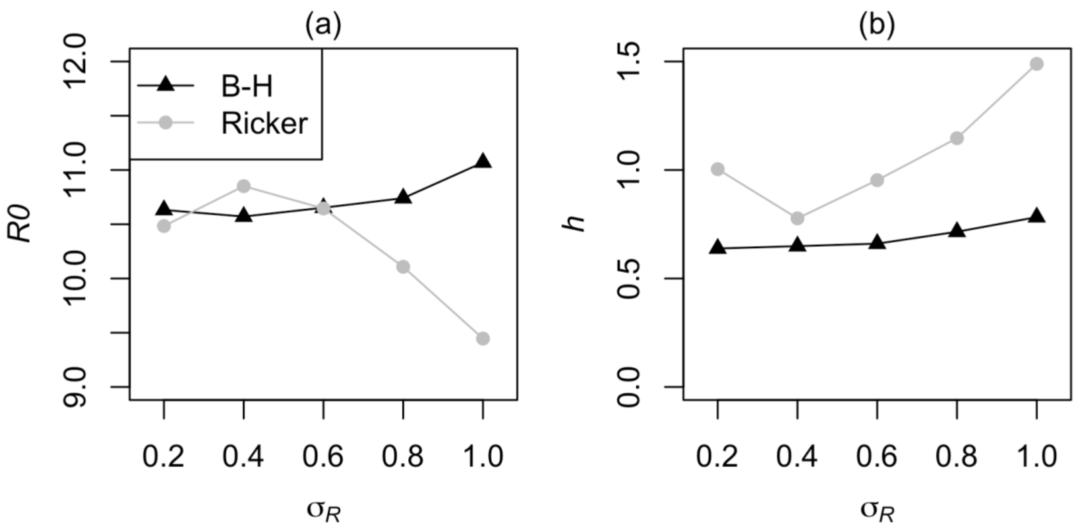

Figure 2 Changes in parameters R_0 (a) and *h* (b) of spawner-recruitment with the σ_R when spawner-recruitment curve is B-H (the black lines with triangle) and Ricker (the grey lines with circle) models.

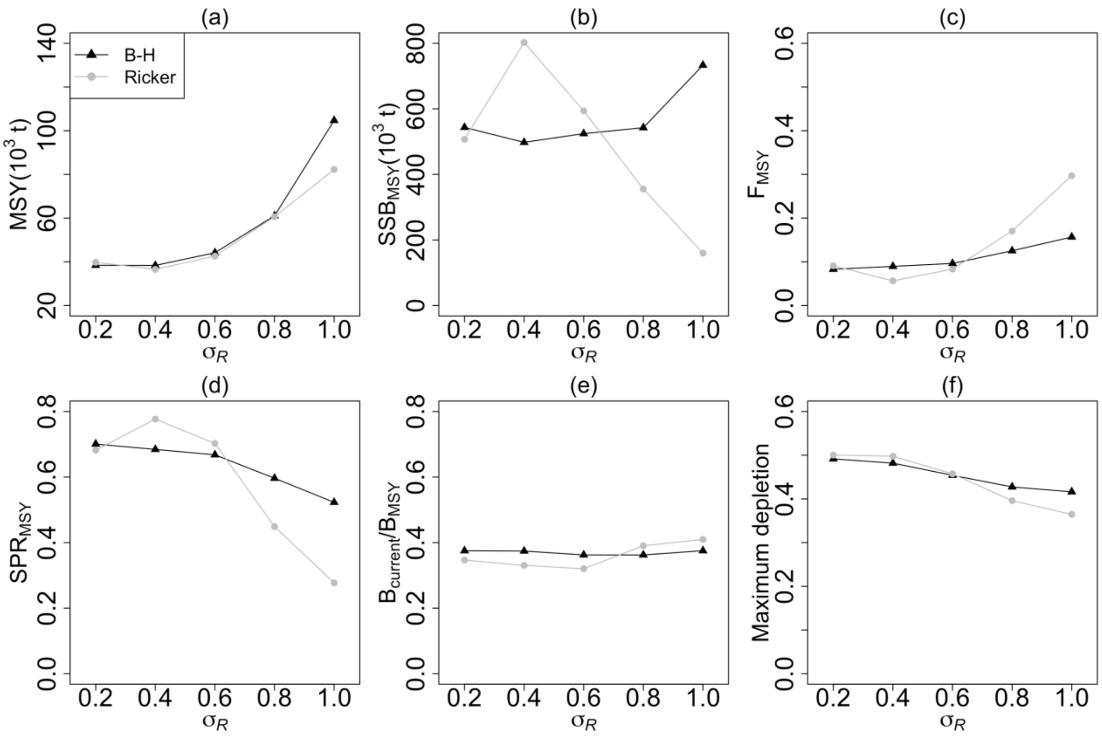

Figure 3 Relationships between the MSY and related management reference points and assumed σ_R (a-d), between the $B_{current}/B_{MSY}$ and assumed σ_R (e), between the maximum depletion and assumed σ_R (f). The black lines with triangle represent relationships deduced from B-H curve; the grey lines with circle represent relationships deduced from Ricker curve.

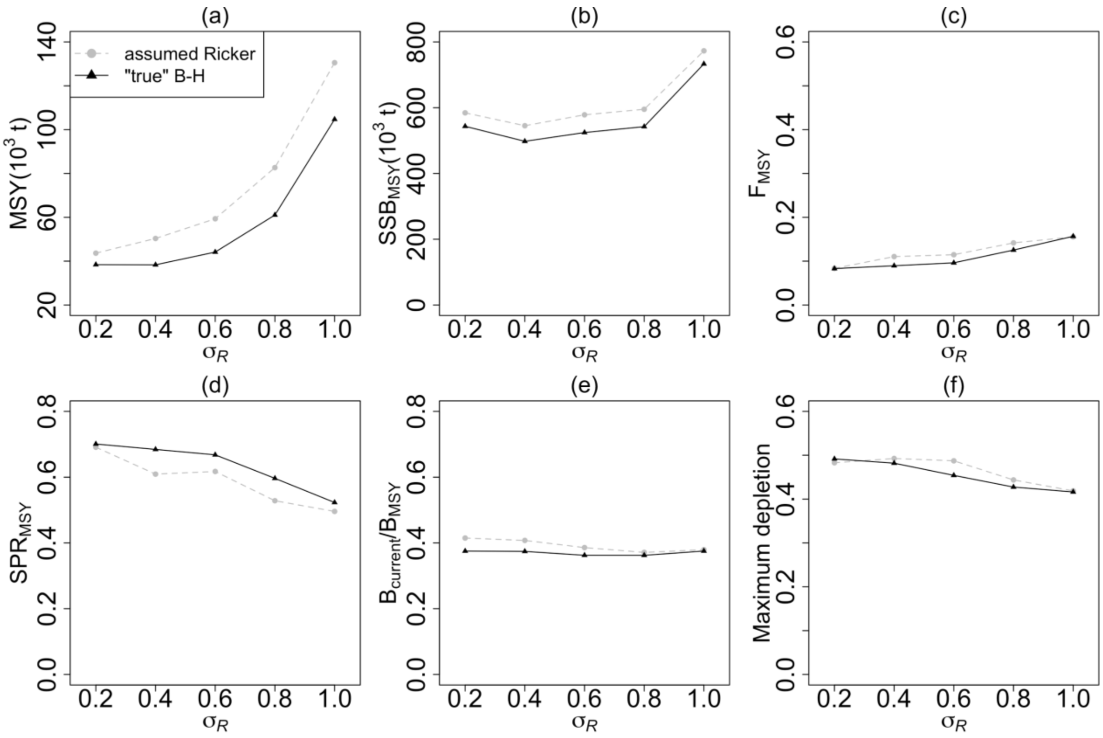

Figure 4 Changes in MSY (a), SSB_{MSY} (b), F_{MSY} (c), SPR_{MSY} (d), $B_{current}/B_{MSY}$ (e) and Maximum depletion (f) when Ricker curve assumed (the grey dotted line with circle) if the “true” spawner-recruitment is B-H curve (the black line with triangle).

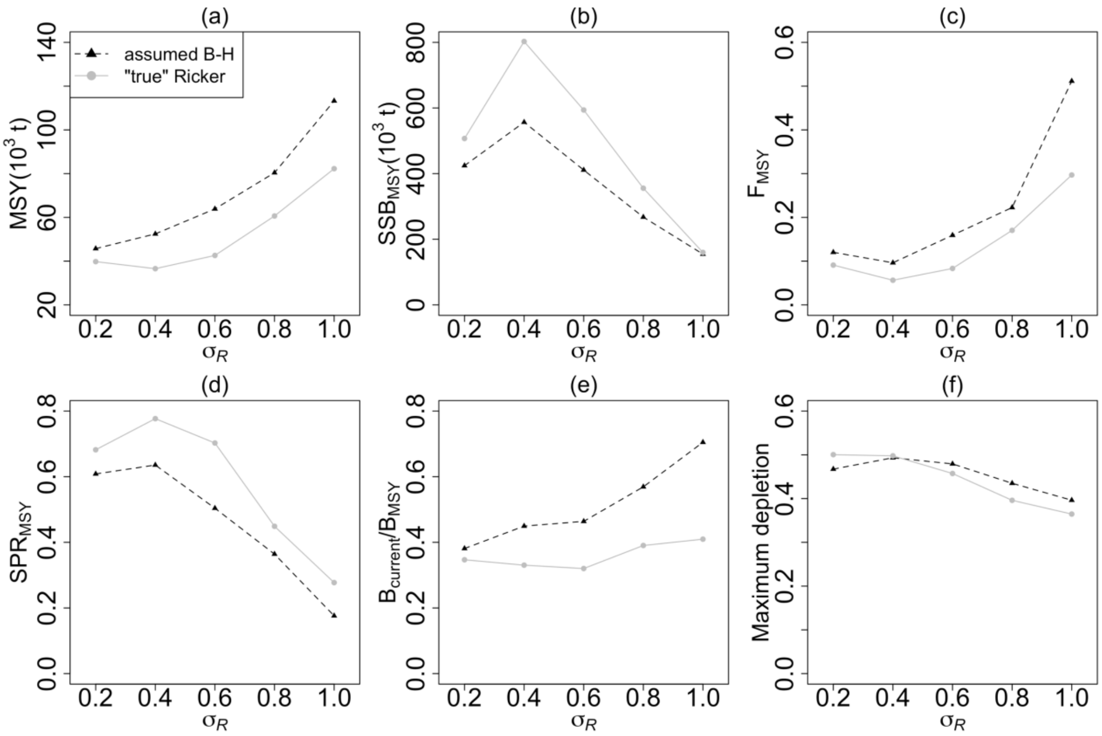

Figure 5 Changes in MSY (a), SSB_{MSY} (b), F_{MSY} (c), SPR_{MSY} (d), $B_{current}/B_{MSY}$ (e) and Maximum depletion (f) when B-H curve assumed (the black dotted line with triangle) if the “true” spawner-recruitment is Ricker curve (the grey line with circle).

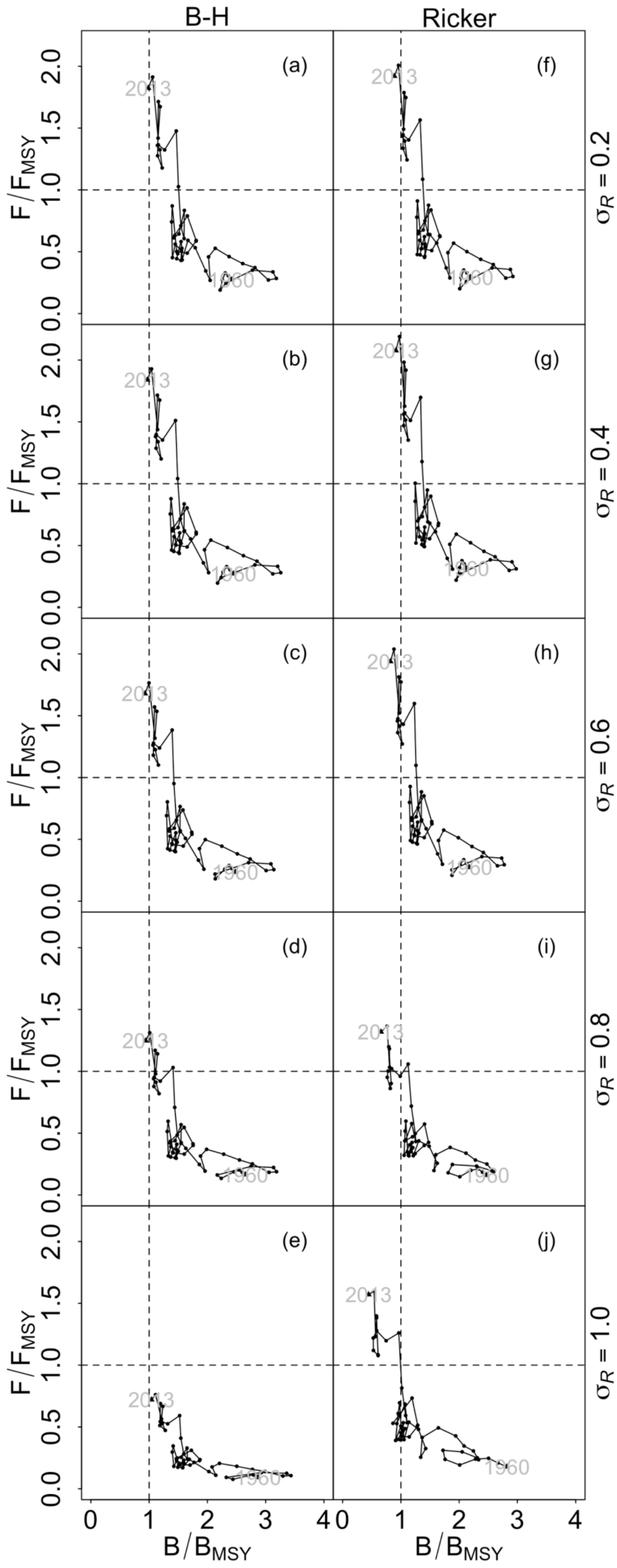

Figure 6 Stock statuses of albacore tuna in Southern Pacific Ocean based on B-H S-R relationship and Ricker S-R relationship with σ_R values ranging from 0.2 to 1.0.