Analysis of sex-specific spawning biomass per recruit of the sailfish (*Istiophorus platypterus*) in the waters off eastern Taiwan

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Abstract—Analyses of sex-specific yield per recruit and spawning stock biomass per recruit were conducted to evaluate the current status of the sailfish (*Istiophorus platypterus*) fishery in the waters off eastern Taiwan. Natural mortality rates estimated from Pauly's empirical equation were 0.26/yr for females and 0.27/yr for males. The current fishing mortality rates were estimated as 0.24/yr and 0.43/yr for females and males, respectively, which are much lower than the estimated $F_{0.1}$ (0.62/yr and 0.79/yr for females and males, respectively) and F_{SSB40} (0.46/yr for females) which are commonly used as target reference points in fisheries management. The effects of the fishing mortality, natural mortality, and age at first capture on the estimates of biological reference points were evaluated by using the Monte Carlo simulation. The results indicate that failure to consider the uncertainty in parameters such as natural mortality or age at first capture may lead to the improper estimation of biological reference points. This study indicates the possibility of current fishing mortality exceeding the target biological reference points may be negligible for sailfish in the waters off eastern Taiwan. However, in view of the recent rapid increase in fishing effort, it is evident that the stock status and development of the fishery need to be closely monitored.

Manuscript submitted 17 July 2008.
Manuscript accepted 28 January 2009.
Fish. Bull. 107:265–277.

Sailfish (*Istiophorus platypterus*) is a circumtropically distributed species (Hoolihan, 2005). Sailfish is a member of the billfish family, Istiophoridae, which also includes marlins and spearfishes, and is considered a bycatch species in commercial fisheries. Off the eastern coast of Taiwan, sailfish are economically important and seasonally abundant from April to October (abundance peaks from May to July). Sailfish are mainly caught by drift gill nets, although some are also caught by set nets, harpoons, and as incidental bycatch in inshore longline fisheries (Chiang, 2004). There are virtually no discards of sailfish in Taiwan. For the past decade, the annual landings of sailfish off Taiwan waters have fluctuated between 500 and 1000 metric tons, of which over 50% have come from waters off Taitung (eastern Taiwan).

Globally, large predatory fish species, including billfish, are declining at alarming rates because of excessive exploitation (Myers and Worm, 2003). Recent increases in the exploitation of billfish stocks by both commercial and recreational fisheries clearly point to the need for accurate assessments, if the goal is to develop sustainable billfish fisheries (Uozumi, 2003). However, because few fisheries target sailfish, assessments have not been conducted, resulting in few or no effective management measures. For sailfish in the Pacific Ocean and Indian Ocean, no assessments have been conducted, and stock status remains unknown. Historical sailfish catch data from the Pacific Ocean are scant, as are data on the length and age composition of the catch. This lack of data precludes the use of most stock assessment tools such as production models and age-structured models (Punt, 1997; Prager and Goodyear, 2001; Liu et al., 2006). However, recent biological studies on sailfish in the waters off eastern Taiwan (Chiang et al., 2004, 2006) have provided an opportunity to apply yield per recruit (Y/R) and spawning biomass per recruit (SSB/R) models (Govender, 1995; Griffiths, 1997) to estimate biological reference points including the fishing mortality rate corresponding to the point where the slope of the yield-per-recruit curve equals 10% of the slope at the origin ($F_{0.1}$; Gulland and Boerema, 1973) and the fishing mortality rate corresponding to a specific percentage (x%) of the spawning biomass per recruit at the unfished level (F_{SSBx}) for the eastern Taiwan sailfish stock. The status of the fishery for this stock could be examined by comparing the fishing mortality at the current level (F_{CUR}) with the biological reference points.

A per-recruit analysis requires information on growth, mortalities, and selectivity of fishing gear. Catch curve analysis (Ricker, 1975) is the most common method employed for estimating total mortality when data on the age composition of catch are available. For a specified natural mortality, F_{CUR} could be computed simply by subtracting the natural mortality from the total mortality. However, in most cases large uncertainty is associated with the estimation of natural mortality and other life history parameters, which can lead to large uncertainty in the estimation of F_{CUR} and biological reference points.

The objective of this study was to evaluate the current status of the sailfish fishery in waters off eastern Taiwan by comparing the current fishing mortality rate (estimated from analyzing length composition data collected from the fishery) with the biological reference points derived from the per-recruit analyses (Butterworth et al., 1989; Sun et al., 2002, 2005). In addition, a Monte Carlo simulation study was conducted for evaluating the influence of uncertainty associated with mortalities and the age at first catch (t_c) on the estimation of biological reference points. This study provides an approach that can be used to assess the status of fisheries for which limited information does not allow us to conduct a full stock assessment.

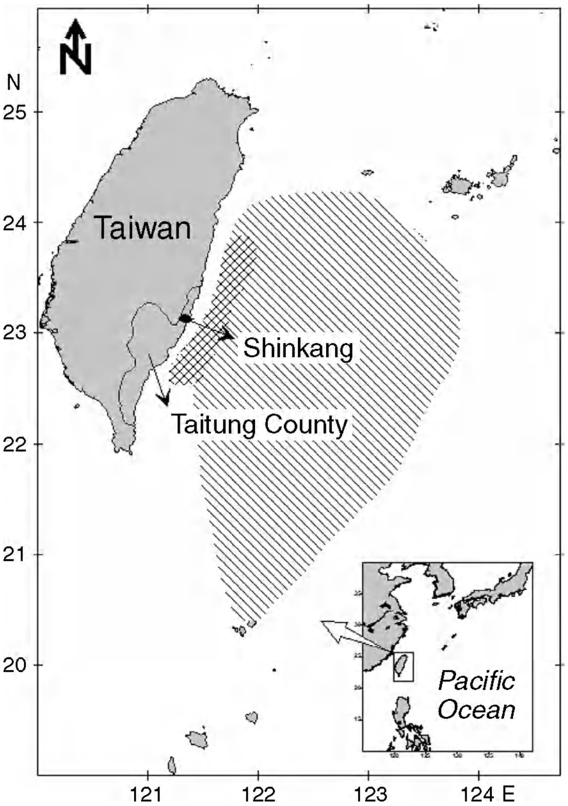

Figure 1

The fishing grounds where sailfish (*Istiophorus platypterus*) are caught as bycatch in the gillnet, harpoon, and longline fisheries based at the Shinkang fishing port of Taiwan. Crosshatched area is where the gillnet and harpoon fisheries take place and the longline fishery takes place in larger area indicated by oblique lines. Samples were collected during the period from July 1998 to July 2005 to estimate biological metrics for per-recruit analyses.

Materials and methods

Length and age composition of the catch

Length composition data were obtained by measuring sailfish landed at the Shinkang fish market in eastern Taiwan (Fig. 1) during the period from July 1998 to July 2005. Specimens were randomly selected from the landings and measured for their lengths and weights. The sex of each specimen was identified from the appearance of its gonads. Samples of the first dorsal fin were taken from 1166 of the sampled individuals for which lengths were measured and used to age the sailfish (Chiang et al. 2004). These subsampled fish were used to construct sex-specific age-length keys, which in turn were used to convert the length-frequency data into age-composition data.

Estimating mortality rates

For each sex, the dynamics of a simulated year class can be projected forward from one year to another by using the exponential survival equation (Ricker, 1975):

$$N_{t+1} = N_t e^{-(M+FS_t)}, \tag{1}$$

where N_t = the number of fish at the beginning of age t;

M = the instantaneous natural mortality rate;

F = t the fishing mortality of fully-recruited fish; and

S_t = the fishing gear selectivity of fish at age t.

Selectivity is the relative vulnerability of different age or size classes to the fishing gear. In this study, we assumed that the selectivity follows a dome-shaped distribution because our length-frequency data were mostly collected from gill nets. This dome-shaped selectivity can be quantified with the following normal distribution density function:

$$S_t = \frac{1}{\sqrt{2\pi}\sigma} e^{\frac{-(t-\mu)^2}{2\sigma^2}}, \tag{2}$$

where μ = the age at the mode of the dome-shaped selectivity; and
σ = the standard deviation of the dome-shaped selectivity.

The expected catch ($\hat{C}_t$) of fish at age t can be estimated based on the catch equation (Ricker, 1975):

$$\hat{C}_t = \frac{FS_t}{M + FS_t} N_t (1 - e^{-(M+FS_t)}), \tag{3}$$

The parameters of N_0, F, μ, and σ can be estimated simultaneously by minimizing the following composite objective function:

$$\sum_t (C_t - \hat{C}_t)^2 + (\max(S_t) - 1)^2, \tag{4}$$

where C_t = the observed numbers of catch at age t.

The F estimated above was considered as the current fishing mortality (F_{CUR}) in this study. The approach outlined above for the catch-curve analysis is similar to the one described in Rudershausen et al. (2008).

A total of 1000 independent bootstrap samples of F were derived from 1000 sets of length-frequency data drawn randomly with replacement from the individuals of original length-frequency data.

Pauly's (1980) empirical equation was used to estimate M for each sex, and the mean sea surface temperature around eastern Taiwan waters fitted to the equation was about 26°C.

Per-recruit analyses

Yield per recruit (Y/R) of sailfish in the waters off eastern Taiwan was estimated from the following model:

$$Y/R = \sum_{t=t_c}^{t_{max}} \left(\overline{W}_t \times \frac{F_t}{Z_t} \times \left(1 - e^{-(FS_t+M)}\right) \times e^{-\sum_{i=0}^{t-1}(FS_i+M)} \right), \tag{5}$$

where $\overline{W}_t$ = the mean weight of fish at age t; and
t_c = the age at first capture.

Mean weight at age was computed as a power function of midyear lower jaw fork length (L_t):

$$W_t = a \times L_t^b, \tag{6}$$

and midyear lower jaw fork length was estimated from the von Bertalanffy growth function

$$L_t = L_\infty \left(1 - e^{-K(t+0.5-t_0)}\right), \tag{7}$$

where K = the growth parameter;
L_∞ = the average asymptotic length; and
t_∞ = hypothetic age at length of 0 (Ricker, 1975; see Table 1).

Table 1

Biological parameters used in the per-recruit analysis for the sailfish (*Istiophorus platypterus*) in the waters off eastern Taiwan during the period from July 1998 to July 2005. VBGF is the von Bertalanffy growth function, L_∞ = the asymptotic length, K = the growth coefficient, t_0 = the hypothetical age at length zero; Length-weight relationship is $W = A \times L^B$, where W = rought weight (in kg) and L = lower jaw fork length (in cm); Maturity fraction parameters r_m = the slope of logistic equation fitted to the maturity data collected, and t_m = the age at 50% sexual maturity.

Parameter	Female	Male
VBGF		
L_∞	250.29 cm	240.539 cm
K	0.138/yr	0.145/yr
t_0	–2.99	–2.781
Length-weight relationship		
A	2.3234×10^{-6}	1.1933×10^{-5}
B	3.1013	2.7828
Maturity fraction		
r_m	1.525	
t_m	5	

The maximum lifespan (t_{max}) of sailfish in the waters off eastern Taiwan was unknown but was estimated by using the empirical relationship of Taylor (1958):

$$t_{\max} = t_0 + \frac{2.996}{K}, \tag{8}$$

The equation for spawning stock biomass per recruit (SSB/R) is

$$SSB/R = \sum_{t=t_m}^{t_{\max}} \left(fr_t \times W_t \times e^{-\sum_{i=t_r}^{t-1}(F_i+M)} \right), \tag{9}$$

where W_t = the mean weight at age t that was calculated from the von Bertalanffy function and length-weight relationship for female sailfish; and
fr = the fraction of female sailfish that are mature.

In this case fr is represented by a logistic equation fitted to maturity data collected from sailfish caught in the eastern waters off Taiwan (Chiang et al., 2004, 2006). The logistic equation can be written as

$$fr_t = \frac{1}{1 + e^{-r_m(t-t_m)}}, \tag{10}$$

where r_m = the slope of the logistic curve; and
t_m = age at which 50% of fish are mature.

Table 2

Scenarios designed to examine the effects of uncertainty of F, M, and t_c on the estimates of biological reference points of sailfish (*Istiophorus platypterus*) in the waters off eastern Taiwan. Scenarios A–D were used to evaluate the effects of changes in a single parameter, scenarios E–H were used to evaluate the results of changes in combinations of two parameters, and scenarios I and J were used to evaluate the results when three parameters were subject to uncertainty. (σ_F=standard deviation from the bootstrapped estimation; M = natural mortality per year; t_c = age at first catch)

	Parameters				
	σ_F		M		
Scenario	Female	Male	Female	Male	t_c
Base	0	0	0.26	0.27	5
A	0.046	0.045	0.26	0.27	5
B	0	0	0.2–0.3	0.2–0.3	5
C	0	0	0.15–0.35	0.15–0.35	5
D	0	0	0.26	0.27	5–7
E	0.046	0.045	0.2–0.3	0.2–0.3	5
F	0.046	0.045	0.15–0.35	0.15–0.35	5
G	0	0	0.2–0.3	0.2–0.3	5–7
H	0	0	0.15–0.35	0.15–0.35	5–7
I	0.046	0.045	0.2–0.3	0.2–0.3	5–7
J	0.046	0.045	0.15–0.35	0.15–0.35	5–7

Biological reference points

The following biological reference points were estimated in order to determine the current status of the sailfish fishery: $F_{0.1}$, F_{SSB25}, and F_{SSB40}. F_{SSB25}, and F_{SSB40} are fishing mortality rates corresponding to the 25% and 40% of the spawning biomass per recruit at unfished level. The choice of 25% or 40% was relatively arbitrary for the fishery, but these values have been used as different levels of reference points for other relatively long-lived marine fishes (e.g., Griffiths, 1997; Kirchner, 2001; Sun et al., 2002, 2005). The spawning potential ratio (*SPR*) is the SSB/R at a given fishing mortality divided by the SSB/R without fishing (Gabriel et al., 1989; Goodyear, 1993; Katsukawa et al., 1999; Watanabe et al., 2000; Sun et al., 2002, 2005) and can be calculated as

$$SPR = \frac{SSB/R}{SSB/R|_{F=0}}. \tag{11}$$

Several authors have advocated designating $F_{0.1}$ or F_{SSB40} as target reference points and F_{SSB25} as a threshold reference point in order to obtain near optimal yields while minimizing the likelihood of stock collapse (Gulland and Boerema, 1973; Deriso, 1987; Hildén, 1993; Sun et al., 2002, 2005). We adopted these target and threshold reference points in this study.

Simulation study

The Monte Carlo simulation approach was applied to evaluate the sensitivity of estimating biological reference points with respect to parameters F, M, and t_c. To quantify the uncertainty of F, F was assumed to follow a normal distribution with a mean and standard deviation (σ_F)—the latter estimated from the bootstrapped estimation of F. However, there was no information on the distribution of M and t_c. We assumed a uniform distribution for M and t_c by referring to the estimation of Pauly's empirical equation and the age at full recruitment from the age composition of sailfish in the waters off eastern Taiwan. The values of M and t_c were sampled randomly from the corresponding uniform distributions defined in Table 2. Ten scenarios were designed to examine the effects of different combinations of the uncertain in parameters F, M, and t_c on the estimation of biological reference points (Table 2). Scenarios A–D were used to evaluate the effects of changes in a single parameter, scenarios E–H were used to evaluate the results of changes in combinations of two parameters, and scenarios I and J were used to evaluate the results when three parameters were subject to uncertainty. For each scenario, 100 replicates of biological reference points were estimated by using the parameters of F, M, or t_c randomly drawn from their assumed distributions. The median and the interquartile range were used to quantify the central tendency and variation for the distributions of estimated biological reference points.

Results

Age composition

Length data were obtained for 12,323 sailfish (3532 females and 8791 males), and age data for 1166 of these fish (446 females and 720 males). The range of lower jaw fork length was 80–239 cm for females and 78–227 cm for males (Fig. 2). Age compositions of samples collected during the entire study period indicated that most sailfish caught off eastern Taiwan are larger than the age at 50% maturity, and peak in length at 5 years (Fig. 3). Accordingly, the estimates of age at full recruitment (t_c) and the sample size during studying periods are shown in Table 3. The estimates of t_c varied from 5 to 7 years for different time periods. Few sampled fishes were older than 11 years for both sexes and hence age 12 and higher were combined into the 12+ group (Fig. 3). The empirical estimates of maximum lifespan (t_{max}) were 13 years for males and 21 years for females.

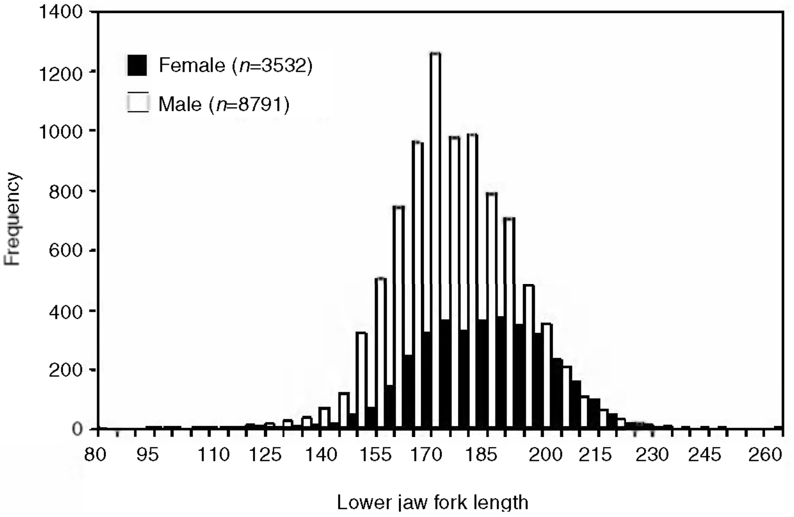

Figure 2

The length-frequency distributions (5-cm intervals) of female (black bars) and male (white bars) sailfish (*Istiophorus platypterus*) in the waters off eastern Taiwan during the period from July 1998 to July 2005. Most fish caught were 160–190 cm in lower jaw fork length.

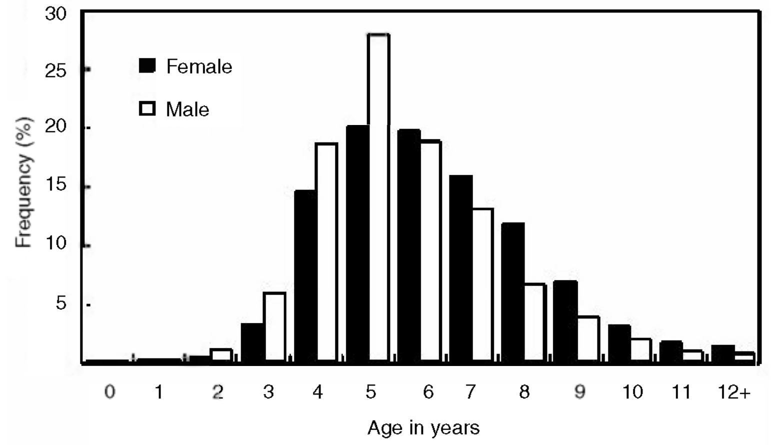

Figure 3

The age-frequency distributions for female (black bars) and male (white bars) sailfish (*Istiophorus platypterus*) in the waters off eastern Taiwan during the period from July 1998 to July 2005. Most fish caught were 4–7 years old.

Mortality rates

The estimates of F were 0.24/yr for females and 0.43/yr for males based on the samples collected during the entire study period. Based on bootstrap analysis, the standard deviation of F was 0.046/yr and 0.045/yr for females and males, respectively. In addition, 79% of bootstrap replicates of t_c were 5 years old and few were 6 or 7 years old. The values of M estimated from the Pauly's empirical equation were 0.26/yr for females and 0.27/yr for males. In this study, therefore, F of 0.24/yr for females and 0.43/yr for males, t_c of 5 years and M of 0.26/yr for females and 0.27/yr for males were set as the base case values for the subsequent analyses. Sensitivity analyses were also conducted for examining the results of Y/R and SPR analyses by assuming values of 0.20, 0.30, and 0.35 for M.

Y/R and *SPR* models and biological reference points

In this study, selectivities for females and males were assumed to be dome-shaped, and the estimated selectivity curves are shown in Figure 4. The estimates of F_{CUR}, $F_{0.1}$, and Y/R under various values of M are summarized in Table 4. For the base case, F_{CUR} (0.24/yr for females and 0.43/yr for males) were substantially lower than the corresponding biological reference points $F_{0.1}$ (0.62 /yr for females and 0.79/yr for males). The estimates of Y/R_{CUR} were 3.37 kg for females and 3.72 kg for males and the estimates of $Y/R_{0.1}$ were 5.11 kg for females and 4.68 kg for males (Fig. 5). Even in the most conservative case, when M was assumed to be 0.2, F_{CUR} was still lower than $F_{0.1}$ for both females and males.

The effect of varying t_c on Y/R is shown in Figures 6 and 7. At low levels of F, Y/R generally increased rapidly over the range of t_c values tested. The values of t_c that maximized the yield per recruit decreased with the magnitude of M and increased with the level of F but typically ranged between 2 and 5 years for females and males.

Table 3

Sample sizes and estimates of age at full recruitment for female and male sailfish (*Istiophorus platypterus*) by year in the waters off eastern Taiwan during the period from July 1998 to July 2005.

	Sample size	Age at full recruitment		Sample size	Age at full recruitment
Female			Male		
1998	131	6	1998	525	6
1999	702	5	1999	1943	5
2000	387	7	2000	578	7
2001	358	6	2001	730	5
2002	349	7	2002	576	5
2004	484	5	2004	1123	5
2005	1121	6	2005	3316	5
Overall	3532	5	Overall	8791	5

Table 4

Estimates of current fishing mortality (F_{CUR}), current yield per recruit (Y/R_{CUR}), and the reference points of $F_{0.1}$ and $Y/R_{0.1}$ at different levels of natural mortality (M) for female and male sailfish (*Istiophorus platypterus*) in the waters off eastern Taiwan during the period from July 1998 to July 2005. $F_{0.1}$ = the fishing mortality rate corresponding to $Y/R_{0.1}$; $Y/R_{0.1}$ = the point of a yield-per-recruit curve where the slope equals 10% of the slope at the origin.

M (1/yr)	F_{CUR} (1/yr)	$F_{0.1}$ (1/yr)	Y/R_{CUR} (kg)	$Y/R_{0.1}$ (kg)
Female				
0.20	0.26	0.54	5.36	7.08
0.26	0.24	0.62	3.37	5.11
0.30	0.22	0.69	2.45	4.13
0.35	0.20	0.80	1.63	3.19
Male				
0.20	0.46	0.70	5.79	6.66
0.27	0.43	0.79	3.72	4.68
0.30	0.41	0.83	3.06	4.04
0.35	0.38	0.91	2.21	3.17

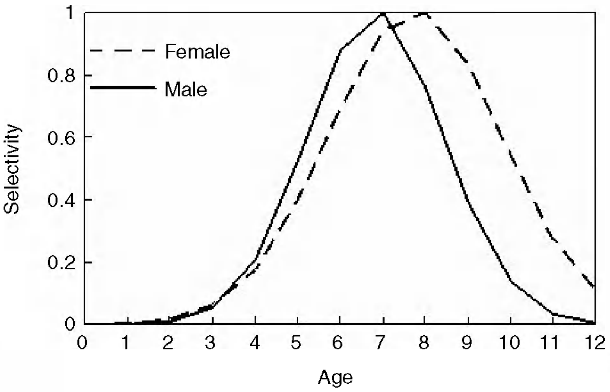

Figure 4

The estimated selectivity curves for female (dashed line) and male (solid line) sailfish (*Istiophorus platypterus*) in the waters off eastern Taiwan. Selectivity is the relative vulnerability of different age or size classes to the fishing gear. In this study, selectivity is assumed to be dome shaped because length-frequency data were mostly collected from gillnets.

The rapid growth and relatively late t_c (5 years) of sailfish in the waters off eastern Taiwan produced low Y/R and high SPR at current fishing mortalities compared with reference points (Figs. 4 and 7). The estimates of F_{SSB25}, F_{SSB40}, SPR and Y/R under the various values of M are summarized in Table 5 and Figure 8. The base-case estimate of F_{CUR} for females (0.24/yr) was lower than the corresponding reference points F_{SSB40} (0.46/yr) and F_{SSB25} (0.94/yr); the current SPR was estimated to be about 57.20% of its unfished level. Under the low value of M (0.2/yr), the estimate of F_{CUR} for females (0.26/yr) was lower than F_{SSB40} (0.36/yr) and substantially lower than F_{SSB25} (0.67/yr). Increasing t_c to older than six years of age would ensure that the SPR was maintained at a value higher than the threshold level (i.e., 25% of its unfished level) at almost any level of fishing mortality (Fig. 9) with relatively little effect on Y/R.

Simulation scenarios

The box plots of the estimates of $F_{0.1}$ and $F_{\mathrm{CUR}}/F_{0.1}$ are shown in Figure 10 for scenarios A–J with the assumption of uncertainty in F, M, and t_c defined in Table 2. Although the medians of these two quantities were close to those of the base case for most scenarios, the variations of these quantities were diverse depending on the assumptions of uncertainty of the parameters. For scenarios A–D with only one parameter subject to uncertainty, the estimates of $F_{0.1}$ were independent of

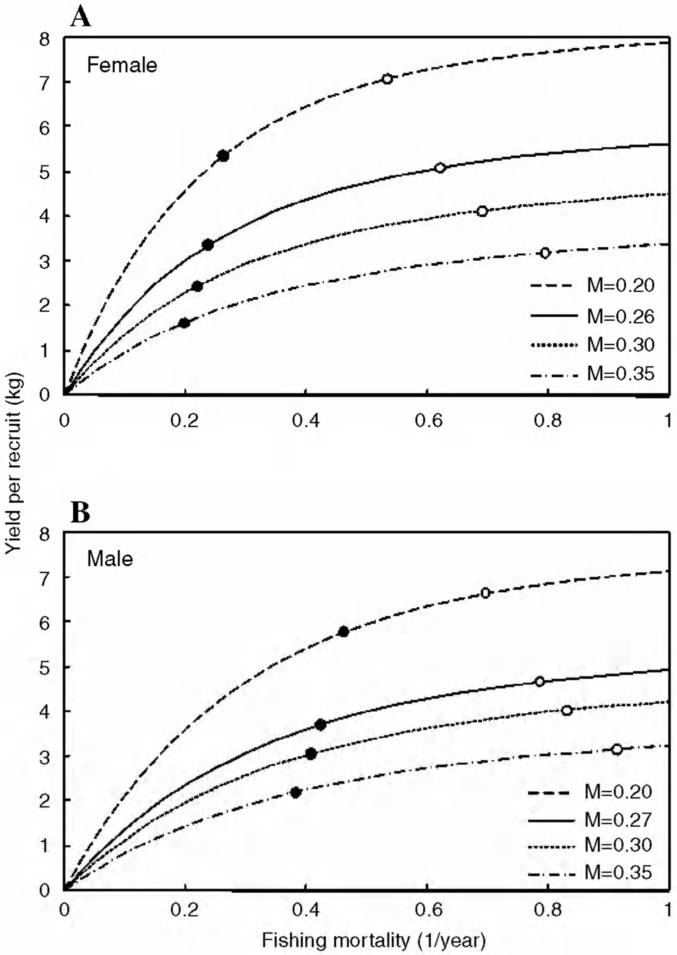

Figure 5

Yield per recruit (Y/R) against fishing mortality per year for female (**A**) and male (**B**) sailfish (*Istiophorus platypterus*) in the waters off eastern Taiwan. ● = F_{CUR}, and ○ = $F_{0.1}$.

Table 5

Estimates of current fishing mortality (F_{CUR}) and the reference points of SSB/R_{SSBx} and SPR at different levels of natural mortality (M) for female sailfish (*Istiophorus platypterus*) in the waters off eastern Taiwan during the period from July 1998 to July 2005. F_{SSBx} = the fishing mortality rate corresponding to SSB/R_{SSBx} ; SSB/R_{SSBx} = a specific percentage (x%) of the spawning biomass per recruit at the unfished level; SPR (spawning potential ratio) = the SSB/R at a given fishing mortality divided by the SSB/R without fishing.

M (1/yr)	F_{CUR} (1/yr)	F_{SSB40} (1/yr)	F_{SSB25} (1/yr)	SSB/R_{CUR} (kg)	SSB/R_{SSB40} (kg)	SSB/R_{SSB25} (kg)	SPR_{CUR} (%)
0.20	0.26	0.36	0.67	32.50	26.56	16.60	48.96
0.26	0.24	0.46	0.94	22.22	15.53	9.71	57.20
0.30	0.22	0.54	1.22	17.42	11.14	6.96	62.57
0.35	0.20	0.70	1.73	12.97	7.52	4.70	68.95

the changes in F but were very sensitive to the uncertainty in M. Adding the uncertainty in t_c resulted in slightly higher estimates of $F_{0.1}$ than that for the base case. Higher estimates of $F_{0.1}$ could have resulted from t_c with values larger than 5 years (base case) selected in this scenario. In the case of this study, higher t_c pro-

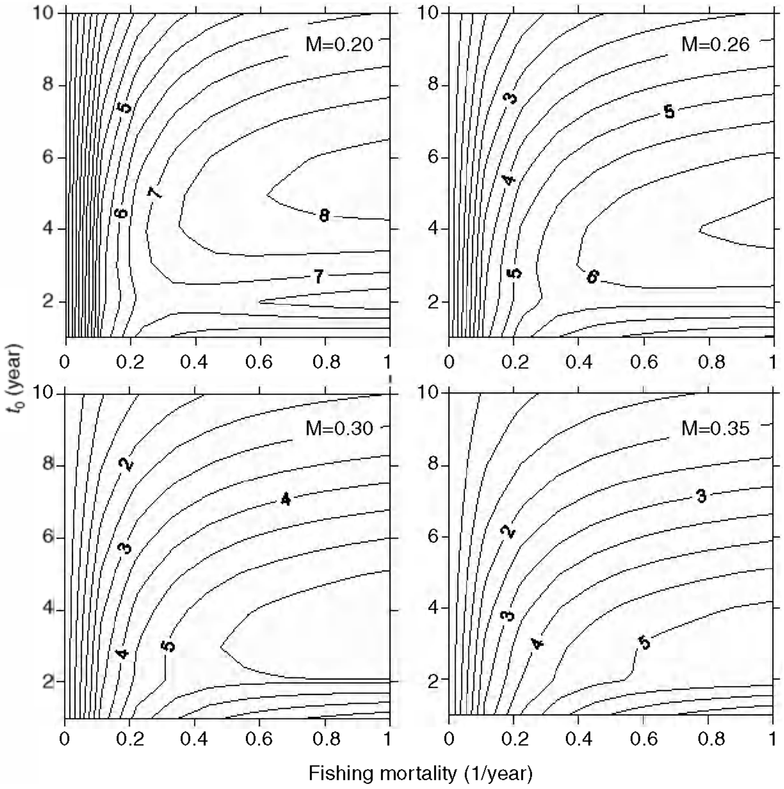

Figure 6

Yield-per-recruit isopleths against fishing mortality per year and age at first capture (t_c) at different levels of natural mortality (M) for female sailfish (*Istiophorus platypterus*) in the waters off eastern Taiwan.

duced higher estimates of $F_{0.1}$ for sailfish in the water of eastern Taiwan. For scenarios E–J that incorporated the combinations of uncertainties in F, M, and t_c, large variations were observed for estimates of $F_{0.1}$ when a higher level of uncertainty was assumed for M (scenarios F, H, and J). Even though combinations of parameters with higher uncertainties were considered, the upper bounds (the third quartile) of $F_{\mathrm{CUR}}/F_{0.1}$ were lower than 1 for all scenarios. This result implied that it was highly unlike that F_{CUR} could exceed $F_{0.1}$. In contrast, the effects of adding uncertainties in F and t_c were relatively minor.

Figure 11 shows the box plots of the estimates of F_{SSB40}, F_{SSB25}, $F_{\mathrm{CUR}}/F_{0.1\mathrm{SSB40}}$, and $F_{\mathrm{CUR}}/F_{0.1\mathrm{SSB25}}$ for scenarios A–J (with uncertainty). Similarly, higher levels of uncertainties in M resulted in higher variations for the estimates of F_{SSB40} and F_{SSB25} (scenarios C, F, H, and J). Moreover, the estimates of F_{SSB40} and F_{SSB25} were obviously higher than those of the base case when the uncertainty in t_c was considered (scenarios D, G, H, I, and J), which might result from female fish younger than t_c being less vulnerable to fishing gear. Therefore, higher values of *SSB*/*R* would be obtained when larger values of t_c were selected and higher estimates of F_{SSB40} and F_{SSB25} were revealed for these scenarios. For all scenarios, the medians of $F_{\mathrm{CUR}}/F_{\mathrm{SSB40}}$ and $F_{\mathrm{CUR}}/F_{\mathrm{SSB25}}$ were 0.71 and 0.37, respectively, which were similar to those of the base case (Table 5). The upper boundaries of $F_{\mathrm{CUR}}/F_{\mathrm{SSB40}}$ and $F_{\mathrm{CUR}}/F_{\mathrm{SSB25}}$ were substantially lower than 1 for all the scenarios and no simulation runs were observed to have the values higher than 1.

Discussion

Mortality rates

The *Y*/*R* curve is so flat-topped that maximum *Y*/*R* cannot be well defined and may not be attained under any practical fishing mortality rate (Fig. 5). Reference points such as $F_{0.1}$, F_{SSB25}, and F_{SSB40} have often been used to develop fishery management strategies. Previous studies have indicated that *Y*/*R* and *SPR* are sensitive to values of *M* (Griffiths, 1997; Kirchner, 2001; Sun et al., 2005). In this study, however, the estimates of F_{CUR} were much lower than the target levels of $F_{0.1}$ or F_{SSB40}, except for the scenario when *M* was assumed at the lower bound of 0.2. Moreover, the estimates of F_{CUR} were never larger than the threshold level of F_{SSB25} even

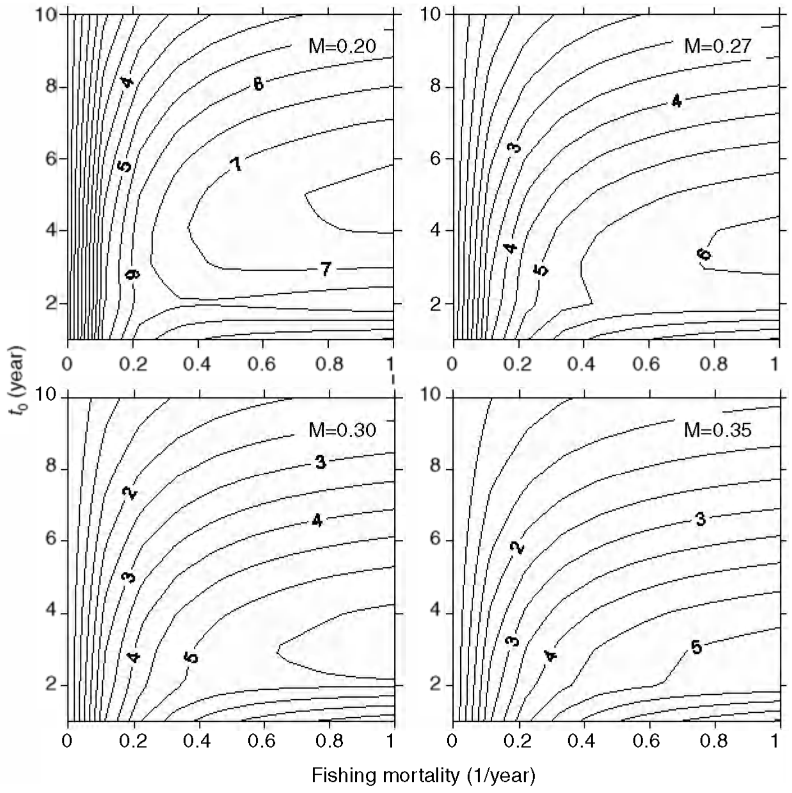

Figure 7

Yield-per-recruit isopleths against fishing mortality per year and age at first capture (t_c) at different levels of natural mortality (M) for male sailfish (*Istiophorus platypterus*) in the waters off eastern Taiwan.

when M was assumed to be 0.2. This result would indicate that the stock of sailfish in the waters off eastern Taiwan appears to be moderately exploited and has relative low risk of being overfishing.

Sex-specific per-recruit analyses and sensitivity analyses

Most assessment methods require historic information on catch, effort, and catch-at-age (or catch-at-length). The lack of long-term fishery statistics usually makes it difficult to evaluate the status of populations exploited by small-scale fisheries or taken incidentally (e.g., Govender, 1995; Barbieri et al., 1997; Griffiths, 1997; Jones and Wells, 2001; Sun et al., 2002, 2005). Per-recruit analyses, which require only parameters related to life span and mortality, combined with an analysis of catch curves, can become an alternative method for evaluating the status of a fishery. Because per-recruit analyses can provide the estimates of biological reference points and the catch curve analysis can yield

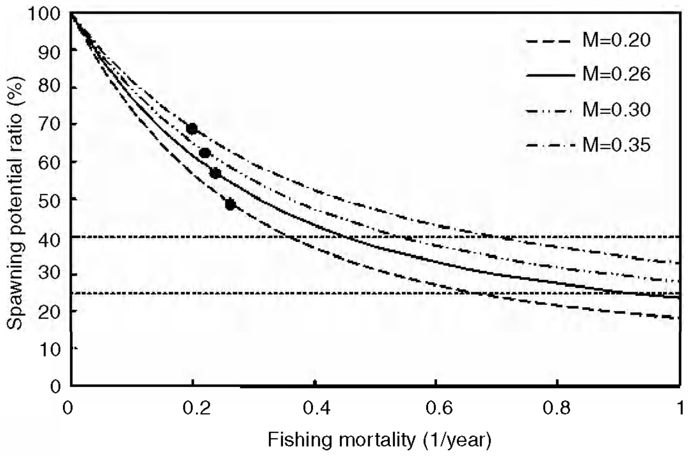

Figure 8

Spawning potential ratio (expressed as a percentage) against fishing mortality for female sailfish (*Istiophorus platypterus*) in the waters off eastern Taiwan where age at first capture (t_c) = 5 years (solid dots are SPR_{CUR} levels; horizontal dashed lines are levels for the biological reference points of F_{SSB40} and F_{SSB25}, and ● = F_{CUR}).

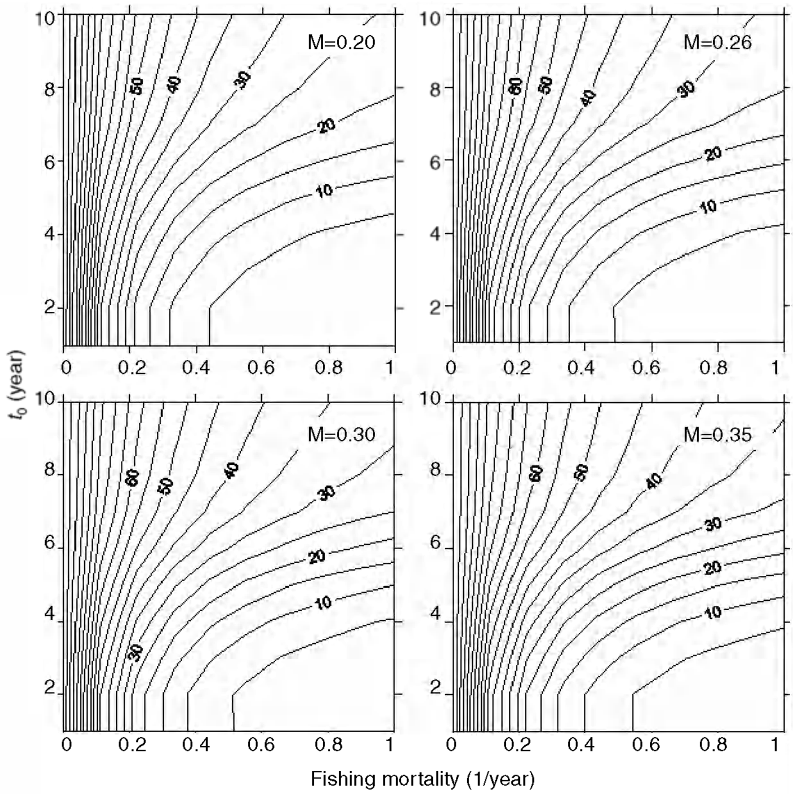

Figure 9

Spawning-potential ratio (*SPR*) isopleths against fishing mortality per year and age at first capture (t_c) at different levels of natural mortality (M) for female sailfish (*Istiophorus platypterus*) in waters off eastern Taiwan.

the estimate of current fishing mortality rate, the status of a fishery can be readily determined by comparing current fishing mortality with the biological reference points. Nevertheless, few results of previous studies have been discussed as to how the biological reference points based on per-recruit analyses were influenced by the uncertainties of biological parameters.

In this study, the effects of F, M, and t_c on the estimates of $F_{0.1}$, F_{SSB40}, and F_{SSB25} were evaluated by using the Monte Carlo simulation method. Although other parameters (e.g., growth) are essential inputs for per-recruit analyses, we focused on the effects of F, M, and t_c which are generally more difficult to estimate owing to a lack of enough auxiliary information (Chen et al., 2007). In addition, the assumption of selectivity of fishing gear could influence the results of per-recruit analyses. Generally, longline selectivity is assumed to be asymptotic and gillnet selectivity is assumed to be dome shaped. In this study, a dome-shaped selectivity was assumed for incorporating into the per-recruit analyses. Sailfish in the waters off eastern Taiwan were exploited by various fishing gears although large proportion of the catch was made by gillnet. However, insufficient length-frequency data recorded by fishing gear lead to difficulty in estimating the selectivity for different fishing gear. Therefore, collecting the information from fishing gear for length-frequency data is necessary to evaluate the influence of different selectivity assumptions on the results of assessment.

Implications of sex-specific assessment and management of the species

Uozumi (2003) indicated that the problems in the stock assessment of sailfish are the inability to obtain reliable biological parameters, standardization of catch per unit of effort, and a mechanism to develop reliable abundance indices. Sailfish are known to be sexually dimorphic (females grow faster and to a larger size than males (Chiang et al., 2004; Hoolihan, 2007), females become mature later than males, and sex ratio varies with length (Chiang, 2004). These attributes indicate that sex-specific assessments should be done to evaluate the status of sailfish. The sex-specific per-recruit analyses with the consideration of parameter uncertainty used in this study provide a method for evaluating management strategies.

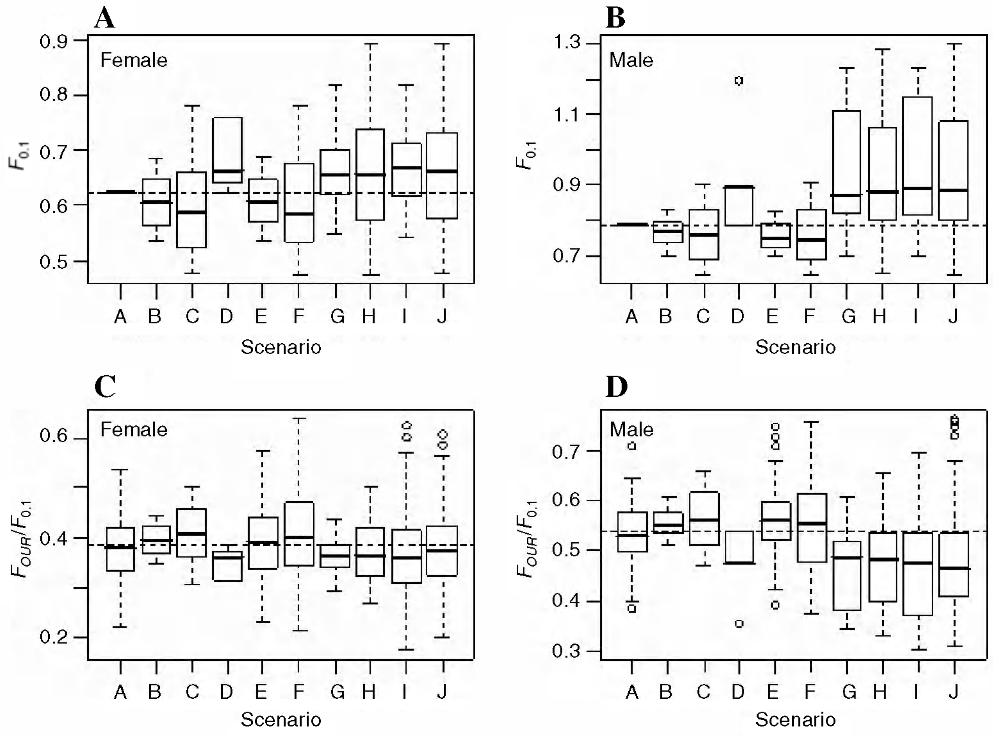

Figure 10

Box plots of the estimates of $F_{0.1}$ and $F_{\mathrm{CUR}}/F_{0.1}$ for scenarios incorporating the uncertainty in total mortality (Z), natural mortality (M) and age at first capture (t_c) for female (**A, C**) and male (**B, D**) sailfish (*Istiophorus platypterus*) in the waters off eastern Taiwan. The center line represents the median and the boxes represent the quartiles. The whiskers extend 1.5 times the interquartile range. Open circles are outliers. Horizontal dash lines indicate the levels of reference points at base case.

There is a possibility that the low F estimates may be an artifact of an influx of fish from outside the study area. Such a bias could occur if the probability that a fish will move from distant waters to within range of the eastern Taiwanese fleet is substantial and increases with the age of the fish (Sun et al., 2005). In principle, estimates for M could be obtained from research (such as tagging studies to determine M; Hampton, 2000). However, in the short to medium term, the values for M will have to be obtained from the results of studies for other stocks of sailfish. They have been similar to those obtained by Pauly's (1980) method. This difference should be evaluated in relation to environmental factors. Although recent analyses of molecular markers do not support recognition of separate Atlantic and Indo-Pacific species of sailfish (Graves and McDowell, 2003), there is no evidence to indicate that sailfish become increasingly likely to migrate to Taiwan with increasing age. Although Prince et al. (2006) examined the tagging results in the eastern Pacific Ocean, they considered this species a single stock. It is unclear whether the sailfish population in the Pacific Ocean comprises a single or multiple stocks, and their regional or global abundance is unknown (Ehrhardt and Fitchett, 2006). A tagging program in which electronic and conventional tags are used to examine the spatial movement patterns and stock structure of sailfish in this geographical region would prove beneficial for the sustainable management of the species.

There are no management measures for sailfish in the waters off eastern Taiwan at present. In the waters off eastern Taiwan, sailfish are targeted by the gillnet fishery and caught incidentally in the longline, harpoon, and set net fisheries. This makes it difficult to effectively control the fishing effort of these fisheries for sailfish. In this case, the isopleths of *SPR* indicate that increasing t_c to an age between six and seven years old would likely result in modest gains in terms of *SPR* (on the order of 40%) and also hedge against recruitment overfishing. For example, the target level of 40% *SPR* could be achieved at even double values of F_{CUR} if t_c for female sailfish was larger than five years (the age at sexual maturity). Of course the efficacy of increasing t_c would be mitigated by any substantial release mortality. At present little is known about the mortality rates of fish released from gillnet and longline vessels operating off eastern Taiwan, and further

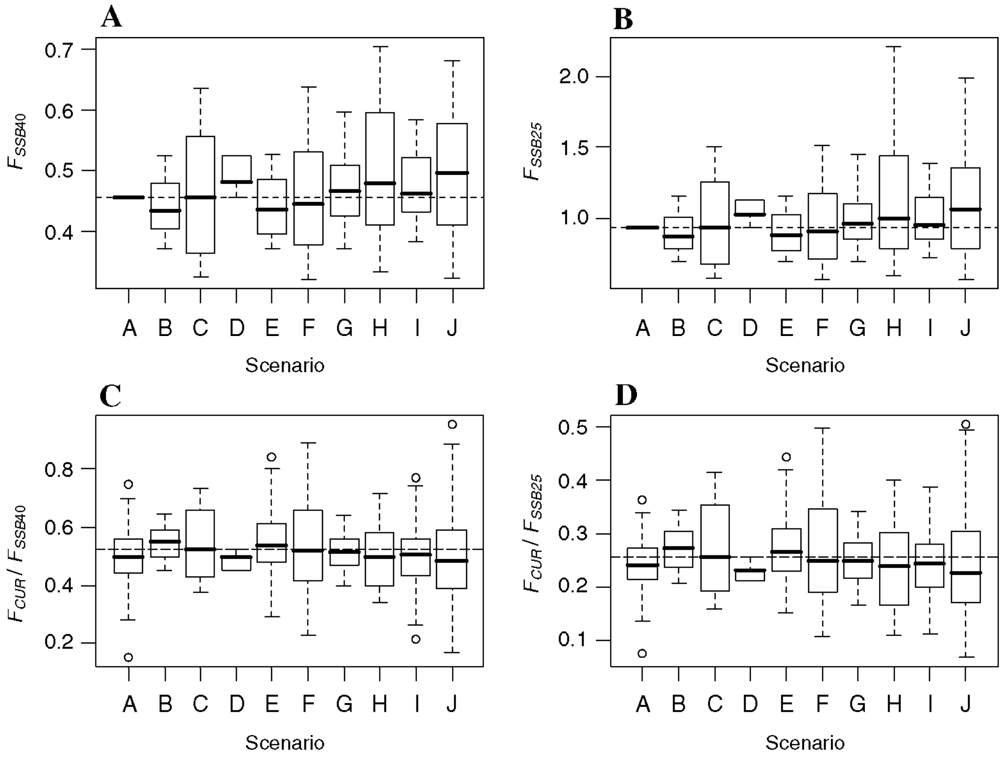

Figure 11

Box plots of the estimates of F_{SSB40}(**A**), F_{SSB25}(**B**), $F_{CUR}/F_{0.1SSB40}$(**C**) , and $F_{CUR}/F_{0.1SSB25}$ (**D**) for scenarios incorporating the uncertainty in total mortality (Z), natural mortality (M), and age at first capture (t_c) for female sailfish (*Istiophorus platypterus*) in the waters off eastern Taiwan. The center line represents the median and the box represents the quartiles. The whiskers extend 1.5 times the interquartile range. Open circles are outliers. Horizontal dashed lines indicate the levels of reference points at base case.

study is needed before we can confidently recommend increasing t_c as a measure to prevent overfishing.

In summary, sex-specific per-recruit modeling coupled with Monte Carlo simulation analyses are effective in evaluating the stock status of billfish because of the sexual dimorphism and uncertainty in key life history and fishery parameters of these species. This study reveals that sailfish in the waters off eastern Taiwan appear to be moderately exploited and have relative low risk of being overfished. However, in view of the recent rapid increase in fishing effort, it is evident that the stock status and development of the fishery need to be closely monitored.

Acknowledgments

We would like to thank two reviewers, Michael H. Prager, NMFS Southeast Fisheries Science Center, and Gerard DiNardo, NMFS Pacific Islands Fisheries Science Center, and one anonymous reviewer for their valuable and constructive comments. We thank Michael Prager for proposing the modified catch-curve method. This study was partially financially supported by the Fisheries Agency, Council of Agriculture, Taiwan, through the grant 93AS-9.1.1-FA-F1(2) to Chi-Lu Sun.

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