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Sex-specific yield per recruit and spawning stock biomass per recruit for the swordfish, *Xiphias gladius*, in the waters around Taiwan

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Abstract

Sex-specific yield per recruit and spawning stock biomass per-recruit analyses were conducted to evaluate the population status of swordfish in the waters around Taiwan. Estimates of the total mortality rate, obtained from length composition data by catch-curve analysis, are on the order of $0.30\,year^{-1}$ for females and $0.35\,year^{-1}$ for males. Pauly's empirical method indicates natural mortality rates of 0.25 and 0.27 for females and males, implying that the current fishing mortality rate on either sex is less than $0.1\,year^{-1}$. This is well below the estimates for the target reference points $F_{40\%}$ ($0.12\,year^{-1}$) and $F_{0.1}$ ($0.20\,year^{-1}$), suggesting the swordfish in the waters around Taiwan are not over-exploited. The spawning potential ratio associated with the current level of exploitation was estimated to be 65% of the pristine level. Isopleths of yield per recruit and spawning stock biomass per recruit generated with various mortality rates suggest that both the yield and spawning biomass per recruit could be increased by raising the age at first capture to a value greater than the age at the onset of sexual maturity.
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1. Introduction

The swordfish (*Xiphias gladius* Linnaeus, 1758) is a cosmopolitan species found in the tropical, subtropical and temperate waters of all oceans (Nakamura, 1985). In the waters around Taiwan, swordfish are taken mainly as a bycatch of tuna longline fisheries, although some are also taken by harpoon, gill net, or set net. During the last decade the landings have become substantial, fluctuating between 600 and 1700 mt. Nevertheless, little information has been collected on the historical fishing effort or length/age composition of the catch owing to the low price swordfish commands in comparison to tuna. Recently, however, several studies have estimated the growth and maturity of swordfish in the waters around Taiwan

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(Sun et al., 2002; Wang et al., 2003), making it possible to apply models of yield per recruit and spawning stock biomass per recruit. The objective of this study was to evaluate the population status of swordfish in the waters around Taiwan by comparing estimates of the current fishing mortality rate derived from samples of length with certain benchmark statistics derived from the per-recruit analyses (Butterworth et al., 1989; Punt, 1993; Govender, 1995; Griffiths, 1997).

2. Materials and methods

2.1. Length and age composition of the catch

Length composition data were obtained by measuring swordfish landed at the three major fish markets in Taiwan (Tungkang, Shinkang and Nanfangao; Fig. 1) during September 1997 to September 2001. On any given day, nearly all the swordfish landed at these markets were measured, weighed and identified to sex. The days of sampling were chosen at random from the total number of days the markets were operating; thus, the frequency distribution of length from the sample ought to resemble closely the frequency distribution for the entire Taiwanese catch.

Some of the length samples were accompanied by samples of the first anal fin, which Sun et al. (2002) used
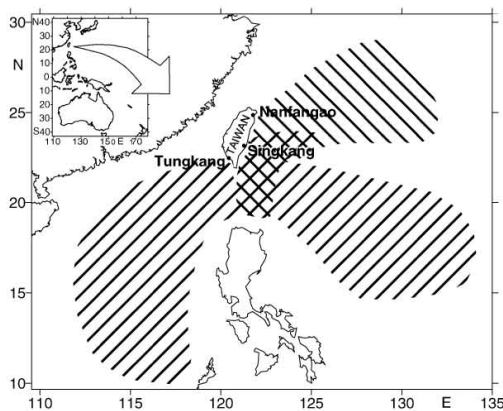

Fig. 1. Fishing ports in Taiwan where the length samples of swordfish were collected. Oblique line areas indicate the fishing grounds of longline fisheries based at Tungkang (left oblique), Nanfangao (right oblique) and Shinkang (intersection).

to age the animals. This subsample of age–length pairs was used to construct sex-specific age–length keys, which in turn were used to convert the length frequency data into age-frequency. Inasmuch as older animals are difficult to age, animals longer than expected for age 9 were lumped together into plus-groups (see discussion in Unpublished, 1999[1]).

2.2. Mortality rate estimation

The total mortality rate Z was estimated from the censored age-frequency distributions discussed above using two forms of catch-curve analyses. The first is a modification of the log-linear regression approach of Chapman and Robson (1960) that accommodates a plus-group. Maximum likelihood estimates for Z (and an intercept parameter α) are found by minimizing the negative log-likelihood expression below:

$$(\ln c_{t_p} - \alpha - \ln(1 - e^{-Z(t_{max} - t_p)}) + Z(t_p - t_f))^2$$
$$+ \sum_{t=t_f}^{t_p-1} (\ln c_t - \alpha - \ln(1 - e^{-Z}) + Z(t - t_f))^2$$

where c_t is the frequency of age t in the sample, t_f the first fully selected age class, t_p the first age in the plus-group (here age 9), and t_{max} the maximum age. For comparison, a second set of estimates was obtained by taking the natural logarithm of the estimates of survival from the method of Robson and Chapman (1961), i.e.:

$$Z = \ln\left(1 + \frac{1 - n_p/n}{\bar{t} - t_f}\right)$$

where n is the total number of observations, n_p the number of observations in the plus-group and $\bar{t}$ the average of the frequency histograms for age classes $\geq t_f$. Both estimators were applied to data aggregated over the duration of the study period, rather than across cohorts, owing to the relatively small sample size.

The maximum lifespan (t_{max}) of swordfish is unknown. For this paper it was calculated using the

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[1] Unpublished, 1999. Detailed report for swordfish. ICCAT SCRS Swordfish Stock Assessment Session, Madrid, Spain, September 27–October 4, 1999, 208 pp.

Table 1
Biological parameters of swordfish in the waters around Taiwan estimated by Sun et al. (2002)

Parameter	Male	Female
L_∞	207.52	267.44
K	0.198	0.13
t_0	−1.955	−2.302
a	1.3528×10^{-6}	
b	3.4297	

empirical relationship of Taylor (1958):

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

where K and t_0 are the von Bertalanffy growth coefficient and intercept at length zero, respectively. Similarly, the natural mortality rate (M) of swordfish is unknown and was calculated using Pauly's (1980) empirical regression on K, asymptotic length (L_∞) and temperature. The von Bertalanffy parameter estimates used are summarized in Table 1. The value for temperature was the annual mean sea surface temperature in the vicinity of Taiwan (about 25 °C, IGOSS, 2002).

2.3. Per-recruit analyses

The model used to estimate the potential yield per recruit (Y/R) of swordfish in the waters around Taiwan was based on the method of Thompson and Bell (1934):

$$\frac{Y}{R} = \sum_{t=t_c}^{t_{\max}} \left(\overline{W}_t \cdot \frac{F_t}{Z_t} \cdot \left(1 - e^{(-F_t + M)}\right) \cdot e^{-\sum_{i=0}^{t-1}(F_i + M)} \right)$$

where $\overline{W}_t$ is the mean weight of fish at age t and F_t the fishing mortality of fish at age t. Mean weight at age was computed as a power function of midyear lower jaw fork length (L_t):

$$W_t = a \cdot L_t^b$$

and midyear lower jaw fork length was computed as a von Bertalanffy function of age

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

(see Table 1).

The fishing mortality rate at age is expressed as the product of age-independent fishing mortality F and age-dependent selectivity S_t:

$$F_t = FS_t$$

No information on the selectivity at age is available for swordfish captured in the waters around Taiwan. For lack of a better alternative, we assume it is knife-edged at various ages at first capture (t_c).

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

$$\frac{\mathrm{SSB}}{\mathrm{R}} = \sum_{t_m}^{t_{\max}} \left(\mathrm{fr}_t \cdot W_t \cdot e^{-\sum_{i=t_r}^{t-1}(F_i + M)} \right)$$

Here W_t is the expected weight at age t from von Bertalanffy curve for female swordfish and fr the fraction of female swordfish that are mature. In this case fr is represented by a logistic equation fitted to maturity data collected from swordfish caught in the waters around Taiwan (Sun et al., 2002; Wang et al., 2003).

$$\mathrm{fr}_t = \frac{1}{1 + e^{-1.899(t-4.693)}}$$

2.4. Reference points

The following reference points were used to determine the status of the stock: $F_{0.1}$, 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 (Gulland and Boerema, 1973); $F_{\max}$, F that produces the maximum yield per recruit; and F_{SPR}, the F that produces a given spawning potential ratio. The spawning potential ratio (SPR) is the SSB/R at 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)

$$\mathrm{SPR} = \frac{\mathrm{SSB/R}}{(\mathrm{SSB/R})_{F=0}}$$

3. Results

Length data were obtained for 968 swordfish (574 females and 394 males) and age data for 629 of these (336 females and 293 males). The range of lower
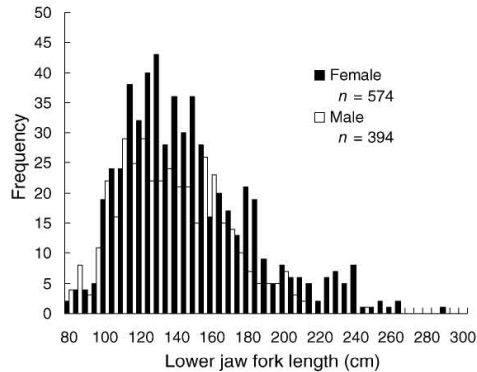
Fig. 2. The length-frequency distributions (5 cm intervals) of swordfish in the waters around Taiwan.

jaw fork length was 75.5–290 cm for females and 78–206 cm for males (Fig. 2). The corresponding age-frequency distributions (Fig. 3) indicate that most of the swordfish caught in the waters around Taiwan were
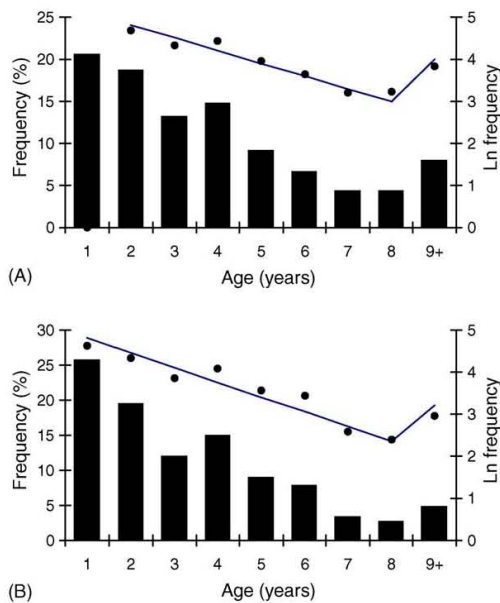

Fig. 3. The age-frequency distributions (bars) and catch curves (circles) of female (A) and male (B) swordfish in the waters around Taiwan.

under the age of 50% maturity, being between 1 and 4 years old, with a peak at age 1. In the case of females, the frequencies of ages 1 and 2 are similar suggesting that age 1 may not yet be fully selected. Accordingly, the age of full recruitment t_c was set to age 1 for males and age 2 for females. The empirical estimates of t_{max} were 13 years for males and 21 years for females. No fish were observed older than these ages in our samples.

The estimates of Z from the censored regression analyses, assuming the above values for t_c and t_{max}, were $0.30 \, year^{-1}$ for females and $0.35 \, year^{-1}$ for males. The Chapman–Robson estimates were similar ($0.30 \, year^{-1}$ for females and 0.33 for males). There were no consistent trends in the residual patterns that would suggest gross violations of the steady state assumption underlying the catch-curve analyses (constant recruitment and mortality rates). Accordingly, we believe the estimates to be a reasonable indication of the average mortality rate during the study period.

The estimates of $F_{current}$, $F_{0.1}$, F_{max} and Y/R (assuming knife-edge selection at the peak ages) under various values of M are summarized in Table 2 and Fig. 4. The values of M estimated by Pauly's empirical equation were $0.25 \, year^{-1}$ for females and $0.27 \, year^{-1}$ for males. Using these as our base, the corresponding estimates for $F_{current}$ are $0.05 \, year^{-1}$ for females and $0.08 \, year^{-1}$ for males, which are substantially lower than the corresponding reference points F_{max} ($0.45 \, year^{-1}$ for females and $0.43 \, year^{-1}$ for males) and $F_{0.1}$ ($0.20 \, year^{-1}$ for both females and males). Consequently, the estimates of Y/R$_{current}$ (6.23 kg for females and 5.89 kg for males) were lower than Y/R$_{max}$ (13.09 kg for females and 9.48 kg for males) and Y/R$_{0.1}$ (11.95 kg for females and 8.51 kg for males).

Table 2
Estimates of current fishing mortality ($F_{current}$) and Y/R (kg) reference points for female and male swordfish taken in the waters around Taiwan

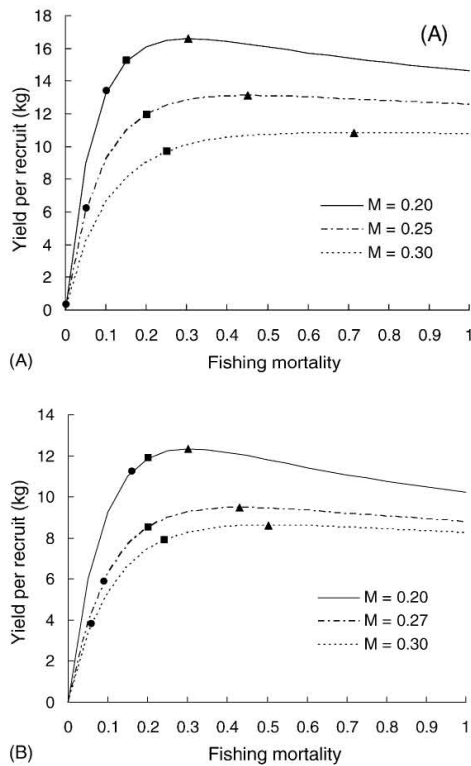| M	$F_{current}$	$F_{0.1}$	F_{max}	Y/R$_{current}$	Y/R$_{0.1}$	Y/R$_{max}$
Female						
0.20	0.10	0.15	0.30	13.38	15.23	16.59
0.25	0.05	0.20	0.45	6.23	11.95	13.09
0.30	0.003	0.25	0.71	0.32	9.68	10.83
Male						
0.20	0.16	0.20	0.30	11.23	11.88	12.35
0.27	0.08	0.20	0.43	5.89	8.51	9.45
0.30	0.06	0.24	0.50	3.81	7.89	8.62

Fig. 4. Yield per recruit against fishing mortality for female (A) and male (B) swordfish in the waters around Taiwan (circles are current levels, squares are $F_{0.1}$ levels, and triangles are F_{max} levels).

The effect of varying the age at first capture on Y/R is demonstrated for various values of M (0.20, 0.25, 0.30 year^{-1} for females and 0.20, 0.27, 0.30 year^{-1} for males) in Fig. 5. The Y/R increased rapidly at low levels of F for most of the range of t_c. 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 2–3 years for males.

The estimates of $F_{25\%}$, $F_{40\%}$, SPR and Y/R (assuming knife-edge selection at the peak ages) under the various values of M are summarized in Table 3 and Fig. 6. Our 'base' estimate of $F_{current}$ for females (0.05 year^{-1}) was lower than the corresponding reference points $F_{25\%}$ (0.19 year^{-1}) and $F_{40\%}$ (0.12 year^{-1})

and the current level of SPR was estimated to be about 65% of the unfished level. Under the low value of M (0.2 year^{-1}), the estimate of $F_{current}$ for females was about the same as $F_{40\%}$ (0.10 year^{-1}). Increasing the age of first capture to between 5 and 7 years of age would ensure that the SPR is maintained between values of 25% and 40% at almost any level of fishing (Fig. 7) with relatively little impact on Y/R.

4. Discussion

Reference points such as $F_{0.1}$, F_{max}, $F_{25\%}$ and $F_{40\%}$ have often been used to develop fishery management strategies. Several authors have advocated designating $F_{0.1}$ or $F_{40\%}$ as target reference points and $F_{25\%}$ as a threshold reference point in order to obtain near optimal yields while ensuring against stock collapse (Gulland and Boerema, 1973; Deriso, 1987; Sissenwine and Shepherd, 1987; Quinn et al., 1990; Hildén, 1993; Leaman, 1993; Mace and Sissenwine, 1993; Rivard and Maguire, 1993; Thompson, 1993; Mace, 1994; Chen, 1997; Griffiths, 1997; Kirchner, 2001). The results of the base Y/R and SPR analyses in this study suggest that the current fishing mortality rates on swordfish in the waters of Taiwan are not only lower than the threshold reference point $F_{25\%}$, but lower than the target reference points $F_{0.1}$ and $F_{40\%}$ as well. This indicates that the stock of swordfish in the waters around Taiwan is not being overfished and may even be somewhat underexploited.

The values used here for our base estimates of natural mortality (0.25 and 0.27 year^{-1} for females and males) are somewhat greater than the value of 0.22 year^{-1} used in previous studies (Boggs, 1989; Joseph et al., 1994; Punt et al., 2001). The value of 0.22 year^{-1} was also obtained by Pauly's (1980) method, but using the unisex growth parameters of Yabe et al. (1959). As it turns out, our conclusions that the stock is not over-fished still holds with a value of M as low as 0.2 year^{-1}, the estimates of current fishing mortality rate remaining at or below all the corresponding reference points.

Our base results suggest that the yield per recruit could be increased by as much as 168% for females and 107% for males simply by increasing the fishing mortality rate to the level corresponding to $F_{40\%}$. Additional gains in Y/R might be achieved by further
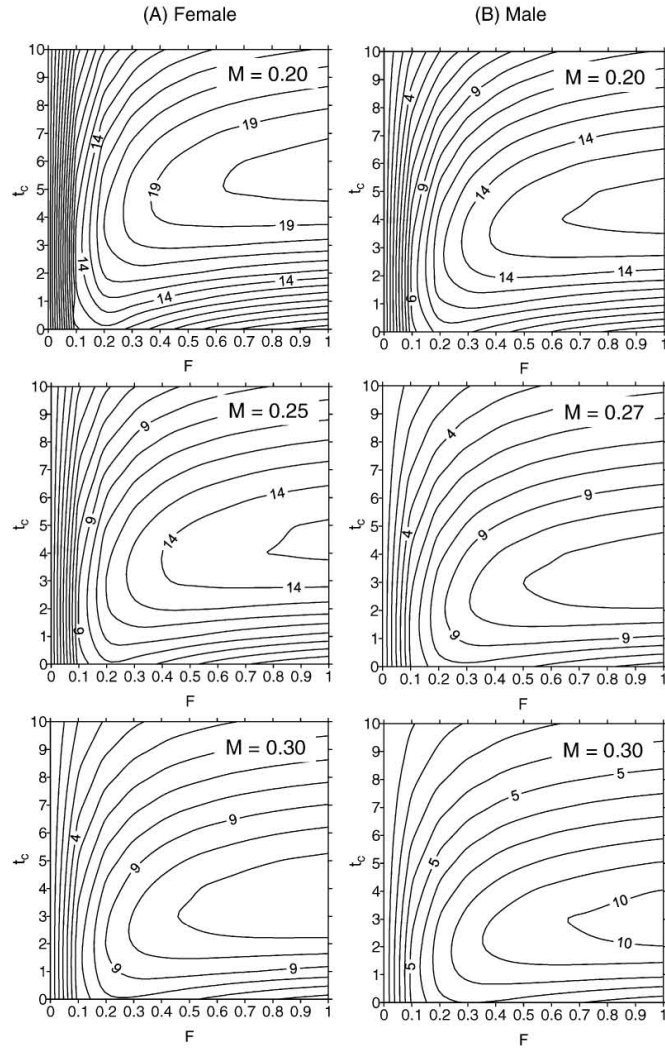
Fig. 5. Isopleths of yield per recruit against fishing mortality (F) and age at first capture (t_c) for female (A) and male (B) swordfish in the waters around Taiwan.

Table 3
Estimates of current fishing mortality ($F_{current}$) and SPR reference points for female swordfish taken in the waters around Taiwan

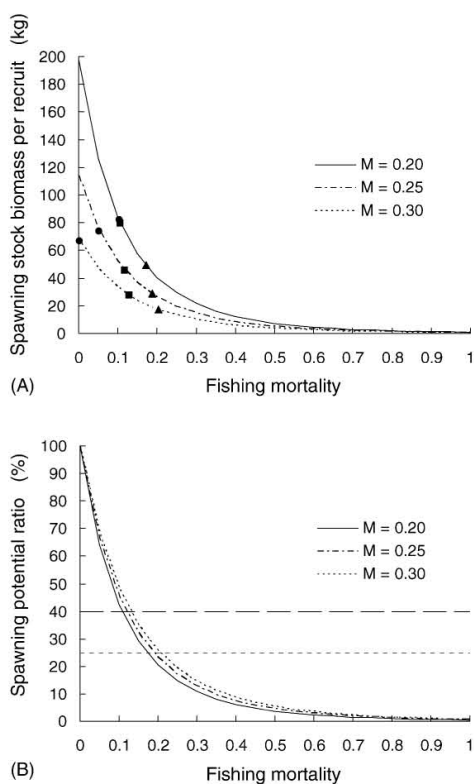| M	$SPR_{current}$	$F_{current}$	$F_{25\%}$	$F_{40\%}$	$Y/R_{current}$	$Y/R_{25\%}$	$Y/R_{40\%}$
0.20	41.43	0.10	0.17	0.1	13.38	15.68	13.59
0.25	64.85	0.05	0.19	0.12	6.23	11.75	9.93
0.30	97.68	0.003	0.20	0.13	0.32	9.11	7.53

Fig. 6. Spawning stock biomass per recruit (A) and spawning potential ratio (B) against fishing mortality for female swordfish in the waters around Taiwan (circles are current levels, squares are $F_{40\%}$ levels, and triangles are $F_{25\%}$ levels).

Fig. 7. Isopleths of spawning potential ratio against fishing mortality (F) and age at first capture (t_c) for female swordfish in the waters around Taiwan.

increases to $F_{0.1}$, but SPR would decrease to under 25% of the pristine condition. If instead M is closer to $0.2\,\text{year}^{-1}$, then the fishery is already close to being fully exploited and increases in F are unlikely to substantially increase the Y/R.

There are no management measures for swordfish in the waters around Taiwan at the present time. The swordfish caught in Taiwanese waters are taken mainly as a bycatch of the tuna longline fishery. This makes it difficult to control the effective fishing effort for swordfish directly. However, it is possible to control the age at first capture indirectly through the use of minimum size limits. In that case, the isopleths of Y/R suggest that increasing t_c to an age between 3 and 5 years old
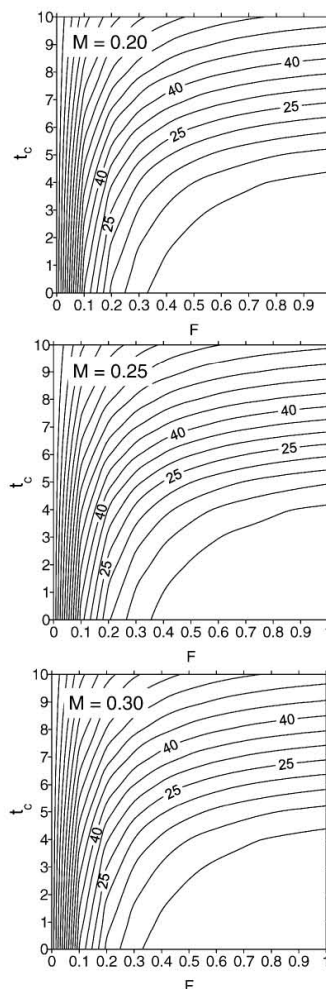
would likely result in modest gains in terms of Y/R (on the order of 10%) while also hedging against recruitment overfishing. For example, the target level of 40% SPR could be achieved at even very large values of F if t_c for female swordfish was larger than 5 years (the age at sexual maturity). Of course the efficacy of increasing t_c would be mitigated by any substantial release mor-

tality. At present little is known about the mortality rates of fish released from longline vessels operating off Taiwan and further study is needed before we can confidently recommend increasing t_c as a measure to prevent overfishing.

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 local Taiwanese fleet is substantial and increases with the age of the animal. While recent analyses of mitochondrial DNA do suggest that the swordfish in the waters around Taiwan are part of a larger population in the northwestern Pacific Ocean (see Reeb et al., 2000), there is no evidence to suggest that swordfish become increasingly likely to migrate to Taiwan with age.

Acknowledgements

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