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Evaluation of the Japanese eel fishery in the lower reaches of the Kao-Ping River, southwestern Taiwan using a per-recruit analysis

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ABSTRACT

Yield-per-recruit (YPR) and spawning stock biomass-per-recruit (SPR) models were used to investigate the impact of fisheries on the yellow and silver eels of the local stock of Japanese eel (*Anguilla japonica*) in the Kao-Ping River (southwestern Taiwan). The current fishery status and uncertainty of biological reference points (e.g., $F_{\max}$, $F_{0.1}$, $F_{40\%}$, and $F_{50\%}$) were assessed using Monte Carlo simulation. Probabilities of the current fishing mortality rate for yellow and silver eels (F_{cur}) being higher than $F_{\max}$ ranged 15–20%, and being higher than $F_{0.1}$ ranged 58–66%. The probabilities of F_{cur} being higher than $F_{40\%}$ and $F_{50\%}$ ranged 26–93% and 73–99%, respectively. The Japanese eel in the lower reaches of the Kao-Ping River appeared to be fully exploited in terms of YPR. This local stock is also subject to a high risk of recruitment overfishing because the contribution of the SPR of the local stock to the entire Japanese eel stock is possibly below a minimal acceptable level (40%). Estimates of $F_{0.1}$ and $F_{\max}$, and to a lesser extent those of $F_{40\%}$ and $F_{50\%}$, were relatively robust, but estimates of the maximal YPR and SPR at F_{cur} were highly sensitive to the uncertainty of the input parameters.

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1. Introduction

Japanese eel (*Anguilla japonica*, Temminck and Schlegel, 1847) is a catadromous fish, widely distributed in Taiwan, China, Korea, and Japan (Tesch, 2003). The population of this eel is considered to be weakly structured between south and north of the distribution (Tzeng et al., 2006) or to be panmictic (Sang et al., 1994; Han et al., 2010). *A. japonica* is the most abundant among the 4 species found in Taiwan (Tzeng, 1982; Tzeng and Tabeta, 1983; Teng et al., 2009), comprising approx. 90% of the total eel catch in the wild (Tzeng et al., 1995; Tzeng and Chang, 2001).

Japanese eel are harvested at different stages (glass eel, elver, and yellow and silver eels) by different fisheries in Taiwan. Glass eels are caught in river mouths during their upstream migration by fishermen using set-nets, fyke-nets, and traps. Yellow and silver eels are mainly harvested in the lower reaches of rivers. The Kao-Ping River contains the largest eel fishery for yellow and silver eels in Taiwan (Lin and Tzeng, 2008). Prices of wild-caught eels are higher than those from aquaculture, consequently encouraging the eel fishery (Chang and Tzeng, 1990). Yellow and silver eels are

by-catch in shrimp nets, which have been widely used for targeting shrimp in Taiwan since 2003 (Lin and Tzeng, 2008). The shrimp net is highly efficient for harvesting eels of >200 mm in total length.

The yellow and silver eel fisheries in Taiwan are unregulated. The elevated exploitation of both yellow and silver eels is likely to lead to reduced local eel stocks in Taiwan and result in insufficient contributions to the total stock (Lin, 2009). Furthermore, eel culture still depends on wild-caught glass eels. Despite the importance of the Japanese eels to the eel fisheries and aquaculture, no quantitative stock assessment has been conducted to date.

Compared to an assembly of different fisheries exploiting a single stock, a small-scale eel fishery such as the Japanese eel fishery in the Kao-Ping River is generally less difficult to assess (Dekker, 2000). For a smaller-scale eel fishery, it is also easier to obtain biological data and implement adequate monitoring plans. Per-recruit analysis (i.e., yield-per-recruit (YPR) and spawning stock biomass-per-recruit (SPR) analyses) is often recommended as a rapid assessment tool for a small-scale fishery (Kruse et al., 2005).

In this study, a per-recruit analysis was used to assess the status of the Kao-Ping River Japanese eel fishery and evaluate the effectiveness of two possible management regulations (minimum and maximum legal lengths) that are commonly used for other eel fisheries (e.g., eel fisheries in New Zealand, Hoyle and Jellyman, 2002). A Monte Carlo simulation study was conducted to evaluate how the uncertainty of input parameters might influence estimates of fishing mortality-based biological reference points and their levels of

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uncertainty. The risk of biological overfishing of this local eel stock was also evaluated, using a stochastic decision-making framework (Helser et al., 2001; Chen and Wilson, 2002; Chang et al., 2009).

2. Materials and methods

2.1. Per-recruit analysis

YPR and SPR analyses of Japanese eel in the study area were conducted using the methodology described in Quinn and Deriso (1999):

$$YPR = \int_{t_r}^{t_{\max}} FN(u)W(u)du = e^{-M(t_c-t_r)}F \times \int_{t_c}^{t_{\max}} e^{-(F+M)(u-t_r)} a[L_{\infty}[1 - e^{-K(u-t_0)}]]^b du \quad \text{and}$$

$$SPR = \int_{t_r}^{t_{\max}} \{N(u)W(u)S(u)\} du$$

$$= \int_{t_r}^{t_c} \left\{ e^{-M(u-t_r)} a[L_{\infty}[1 - e^{-K(u-t_0)}]]^b \right. \\ \times \left. \frac{1}{1 + e^{[\beta_0 + \beta_1 L_{\infty}(1 - e^{-K(u-t_0)})]}} \right\} du \\ + \int_{t_c}^{t_{\max}} \left\{ e^{-(F+M)(u-t_r)} a[L_{\infty}[1 - e^{-K(u-t_0)}]]^b \right. \\ \times \left. \frac{1}{1 + e^{[\beta_0 + \beta_1 L_{\infty}(1 - e^{-K(u-t_0)})]}} \right\} du;$$

where the population growth in number is assumed to be exponential, the weight–length relationship to be allometric, and the length–age relationship to be a von Bertalanffy growth function. The maturation process is defined as the silvering process and was assumed to follow a logistic curve. Symbols are defined in the Appendix A. The selection curve of the shrimp net is assumed to be “knife-edged”, with eels of >200 mm in length being fully vulnerable (Lin and Tzeng, 2008).

Sexes were pooled in the YPR analysis because eel fishermen do not currently separate females from males at the time of harvest, i.e., the fishing mortality (F) cannot be separately specified for males and females. However, female biomass might be more closely associated with egg production, and females dominated (>70%) the studied stock (Han and Tzeng, 2006). Females also grow and mature differently from males (Han et al., 2003; Lin and Tzeng, 2009b), and therefore the SPR analyses were separately carried out by sex.

Four fishing mortality-based biological reference points (F_{BRP}) of $F_{\max}$, $F_{0.1}$, $F_{40\%}$, and $F_{50\%}$, were estimated using per-recruit analysis. $F_{\max}$ and $F_{0.1}$ are defined as the fishing mortality rates corresponding to the maximum value of the YPR function and the fishing mortality at which the slope of the YPR function is 10% of that at $F=0$, respectively (Deriso, 1987). $F_{40\%}$ and $F_{50\%}$ are fishing mortality rates respectively corresponding to 40% and 50% of the spawning stock biomass-per-recruit at unfished levels (Goodyear, 1993). Although the International Council for the Exploitation of the Seas (ICES, 2002) suggests $F_{30\%}$ and $F_{50\%}$ as the limit and precautionary reference points for European eel (*A. anguilla*), a more-conservative limit level of 40% of the SPR was chosen given the variability in glass eel recruitment in Taiwan (Tzeng, 2006), as suggested by Clark (1993, 2002). Key YPR and SPR values for evaluating a fishery's status, namely the maximal YPR ($YPR_{\max}$), the SPR in the absence of exploitation of yellow and silver eels (SPR_0) and at current fishing mortality ($SPR_{F_{cur}}$), and the relative SPR ($\%SPR = SPR_{F_{cur}} \times SPR_0^{-1} \times 100\%$), were also calculated. The integrals of the YPR and SPR functions were computed using the R

Table 1

Formulae, parameter estimates, and corresponding variances (σ^2) of sex-specific length–weight relationships, von Bertalanffy growth functions, mortality rates, and maturation parameters for *Anguilla japonica*. W_t , L_t , N_t , and S_t are the weight, length, population size, and proportion of silver eels in the population at time t . N_r is the population size recruiting to the fishing ground. $\rho_{X,Y}$ is the correlation between variables X and Y .

Formula	Parameter	Female	Male
Length–weight relationship			
$W_t = aL_t^b e^{\varepsilon_{LW}}$	a	4.56×10^{-8}	1.61×10^{-7}
	b	3.55	3.34
$\varepsilon_{LW} \sim N(0, \sigma_{LW}^2)$	σ_{LW}^2	3.93×10^{-2}	2.74×10^{-2}
Growth			
$L_t = L_{\infty}[1 - e^{-K(t-t_0)}]e^{\varepsilon_{GR}}$	L_{∞} (mm)	1023.7	758.7
	K (yr $^{-1}$)	0.118	0.169
	t_0 (yr)		−0.69
$\varepsilon_{GR} \sim N(0, \sigma_{GR}^2)$	σ_{GR}^2		3.10×10^{-2}
Mortality of yellow and silver eels			
$N_t = N_r e^{-[(F_{cur}) + (M + \varepsilon_M)](t-t_r)}$	F (yr $^{-1}$)		0.120
	$\sigma_{F_{cur}}^2$		1.06×10^{-3}
	M (yr $^{-1}$)		0.177
	σ_M^2		1.98×10^{-5}
	$\rho_{GR,M}$		0.8
Maturation (silvering)			
$S_t = \frac{1}{1 + e^{[\beta_0 + \varepsilon_{\beta_0}] + L_t(\beta_1 + \varepsilon_{\beta_1})}}$	β_0	−13.31	−8.92
	$\sigma_{\beta_0}^2$	1.36	4.08
	β_1 (mm $^{-1}$)	2.15×10^{-2}	1.75×10^{-2}
	$\sigma_{\beta_1}^2$	4.04×10^{-6}	1.60×10^{-5}
$\varepsilon_{\beta_0} \sim N(0, \sigma_{\beta_0}^2)$, $\varepsilon_{\beta_1} \sim N(0, \sigma_{\beta_1}^2)$	ρ_{β_0, β_1}		−0.9
Maximum observed length (mm)		880	700
Maximum age ($t_{\max}$, yr)		15.95	14.45
Length at recruitment (L_r , mm)			55
Age at recruitment (t_r , yr)			0.489
Length at first capture (L_c , mm)			200

function, *integrate* (vers. 2.8.1, Owen, 2006). F_{BRP} and key YPR and SPR values were calculated using Newton's method in R.

Two possible management regulations for the management of the eel fishery, minimum ($L_{\min}$) and maximum ($L_{\max}$) legal lengths, were incorporated in the YPR and SPR models by setting F equal to 0 when the total length of a fish was $<L_{\min}$ or $>L_{\max}$. The minimum length of eels caught by the current unregulated fishery is 200 mm (Lin and Tzeng, 2008), and thus $L_{\min}$ was set to 200–700 mm for both sexes. $L_{\max}$ decreased from 800 to 400 mm in females and 700 to 300 mm in males to accommodate different asymptotic (L_{∞}) and maximum observed lengths between the sexes (Table 1).

2.2. Incorporation of uncertainty in the parameter estimation

The above per-recruit analysis is deterministic and ignores parameter uncertainty. Therefore, a Monte Carlo simulation approach was used to account for parameter uncertainty (cf. Chen and Wilson, 2002; Grabowski and Chen, 2004; Chang et al., 2009). To quantify the uncertainty of the parameters, log-normal multiplicative errors were added to the weight-at-length and length-at-age relationships: $W' = aL^b e^{\varepsilon_{LW}}$ and $L'_t = L_{\infty}[1 - e^{-K(t-t_0)}]e^{\varepsilon_{GR}}$, respectively. The uncertainty in M and the maturation parameters (β_0 and β_1) were modeled as additive normal errors, i.e. $M' = M + \varepsilon_M$, $\beta'_0 = \beta_0 + \varepsilon_{\beta_0}$ and $\beta'_1 = \beta_1 + \varepsilon_{\beta_1}$. The current fishing mortality (F_{cur}) was generated from a gamma distribution $F_{cur} \sim \Gamma(\alpha, \beta)\alpha\beta$, where $\alpha\beta = \hat{F}_{cur}$, $\alpha\beta^2 = \hat{\sigma}_{F_{cur}}^2$ to prevent unrealistic values (i.e., $F_{cur} < 0$).

To account for the likely correlation between life history parameters (Chen, 1996), the growth (in length) and natural mortality parameters were assumed to be correlated, as were the maturation

parameters:

$$\begin{bmatrix} \varepsilon_{GR} \\ \varepsilon_M \end{bmatrix} \sim N_2(\mathbf{0}, \Sigma_{GR,M}), \text{ where } \Sigma_{GR,M} = \begin{bmatrix} \sigma_{GR}^2 & \rho_{GR,M}\sigma_{GR}\sigma_M \\ \rho_{GR,M}\sigma_{GR}\sigma_M & \sigma_M^2 \end{bmatrix} \text{ and} \\ \begin{bmatrix} \varepsilon_{\beta_0} \\ \varepsilon_{\beta_1} \end{bmatrix} \sim N_2(\mathbf{0}, \Sigma_{\beta_0,\beta_1}), \text{ where } \Sigma_{\beta_0,\beta_1} = \begin{bmatrix} \sigma_{\beta_0}^2 & \rho_{\beta_0,\beta_1}\sigma_{\beta_0}\sigma_{\beta_1} \\ \rho_{\beta_0,\beta_1}\sigma_{\beta_0}\sigma_{\beta_1} & \sigma_{\beta_1}^2 \end{bmatrix};$$

where $\rho_{GR,M}$ and ρ_{β_0,β_1} were respectively the correlations between growth and natural mortality, and between the maturation parameters. ρ_{β_0,β_1} was derived from our catch data (Lin, 2009). A reference value for $\rho_{GR,M}$, the correlation between natural mortality and growth in Japanese eels, was set to the estimate reported by Pauly (1980).

Growth parameters were derived from aging data based on otoliths (Lin and Tzeng, 2009a, b), fishing and natural mortality rates from a tag-recapture experiment (Lin et al., 2010a), maturation parameters from catch records for 1998–2008 (Lin, 2009), and other parameters from Cheng and Tzeng (1996) and Lin and Tzeng (2008) (Table 1). Details can be found in those earlier studies.

The generated parameters were used to calculate the biological reference points and key YPR and SPR values. Preliminary runs suggested that outputs based on 5000 replicates were identical up to the sixth decimal place; we therefore used 5000 replicates for all Monte Carlo analyses. Empirical distributions of F_{BRP} and key YPR and SPR values were estimated to determine the uncertainty associated with these quantities.

A stochastic decision-making framework (Helser et al., 2001; Chen and Wilson, 2002) was applied to assess this eel stock because there is uncertainty in estimates of both the current fishing mortality (F_{cur}) and F_{BRP} (e.g., F_{max}). The F_{BRP} value at a given decision confidence, $x\%$ ($F_{BRP,x\%}$), was defined as the F_{BRP} value such that $x\%$ of all possible values of F_{BRP} was smaller than $F_{BRP,x\%}$, i.e., $P[F_{BRP} \leq F_{BRP,x\%}] = x\%$. The risk of biological overfishing, defined as the conditional probability of F_{cur} being larger than F_{BRP} under a given decision confidence, $x\%$ ($P[F_{cur} > F_{BRP} | F_{BRP} = F_{BRP,x\%}]$), was then computed from $F_{BRP,x\%}$, and the empirical distribution for F_{cur} . Therefore, the more confident (higher x) we are about F_{BRP} , the higher the value of $F_{BRP,x\%}$, and the smaller the probability that F_{cur} will be larger than $F_{BRP,x\%}$. Consequently, a higher level of decision confidence results in a lower risk of biological overfishing.

Fig. 1. Calculated yield-per-recruit (YPR, black curves and left y-axis) and relative spawning stock biomass-per-recruit (%SPR, gray curves and right y-axis) of Japanese eel in the study region. Sexes were pooled in the YPR and separated in the %SPR analyses. The vertical black line indicates the current fishing mortality (0.12 yr^{-1}).

Table 2

Estimated fishing mortality (F)-based biological reference points (F_{max} , $F_{0.1}$, $F_{40\%}$, and $F_{50\%}$; yr^{-1}) for the Japanese eel fishery in the lower reaches of the Kao-Ping River in southern Taiwan based on the yield-per-recruit (YPR) and spawning stock biomass-per-recruit (SPR) models. F_{cur} is the current fishing mortality rate (yr^{-1}). YPR_{max} is the maximal YPR value (g ind^{-1}); $SPR_{F_{cur}}$ is the SPR values at $F = F_{cur}$ (g ind^{-1}); SPR_0 is the SPR values at $F = 0$ (g ind^{-1}); and the relative SPR (%SPR) is equal to $SPR_{F_{cur}} \times SPR_0^{-1} \times 100\%$. Sexes were pooled for F_{cur} , F_{max} , $F_{0.1}$, and YPR_{max} .

	Female	Male
F_{cur}		0.120
F_{max}		0.165
$F_{0.1}$		0.115
$F_{40\%}$	0.094	0.113
$F_{50\%}$	0.070	0.084
YPR_{max}		61.4
$SPR_{F_{cur}}$	329.2	214.9
SPR_0	1048.8	565.4
%SPR	31.4	38.0

3. Results

3.1. Deterministic YPR and SPR analyses

F_{max} was 0.165 yr^{-1} corresponding to a maximum YPR value (YPR_{max}) of $61.4 \text{ g individual}^{-1}$ [$(\text{ind})^{-1}$], and $F_{0.1}$ was 0.115 yr^{-1} (Table 2). The current fishing mortality rate on yellow and silver eels ($F_{cur} = 0.120 \text{ yr}^{-1}$) slightly exceeded $F_{0.1}$, but was smaller than F_{max} .

$F_{40\%}$ was 0.094 and 0.113 yr^{-1} for females and males respectively, while the corresponding values for $F_{50\%}$ were 0.070 and 0.084 yr^{-1} (Table 2), all of which are smaller than F_{cur} . SPR was higher for females ($SPR_0 = 1048.8 \text{ g ind}^{-1}$) than for males (565.4 g ind^{-1}) in the absence of exploitation, but the SPR of females was slightly lower than that of males when fishing mortality increased (Fig. 1). Under F_{cur} , the SPR declined to 31% and 38% of SPR_0 in females and males, respectively.

3.2. Evaluation of minimum legal lengths

YPR increased with F and L_{min} . At F_{cur} , the YPR was maximized (at around 70 g ind^{-1}) at an L_{min} of around 500 mm . YPR values reached a plateau of 100 g ind^{-1} when L_{min} was 600 – 700 mm and F was $>0.4 \text{ yr}^{-1}$ (Fig. 2). %SPR increased with increasing L_{min} for both sexes (Fig. 3). At F_{cur} , the L_{min} that produced the highest YPR values (500 mm) resulted in %SPR being slightly higher than 50% for both sexes. However, optimizing YPR (L_{min} 600 – 700 mm , $F > 0.4 \text{ yr}^{-1}$)

Fig. 2. Isopleths of sex-pooled yield-per-recruit under different combinations of fishing mortality rates and minimum legal sizes (L_{min}). No minimal legal size is set, but current fishing practice conforms to a minimum size of 200 mm . The black broken line indicates current fishing mortality.

Fig. 3. Isopleths of the relative spawning stock biomass-per-recruit under different combinations of fishing mortality rate and minimum legal size (L_{min}) for (a) females and (b) males. The black broken line indicates current fishing mortality.

Fig. 5. Isopleths of relative spawning stock biomass-per-recruit data under different combinations of fishing mortality rate and maximum legal size (L_{max}) for (a) females and (b) males. The black broken line indicates current fishing mortality.

Fig. 4. Isopleths of sex-pooled yield-per-recruit data under different combinations of fishing mortality rate and maximum legal size (L_{max}). The black broken line indicates current fishing mortality.

might result in %SPR being <50% in females (Fig. 3a) and <60% in males (Fig. 3b).

3.3. Evaluation of maximum legal lengths

Compared to L_{min} , implementation of a maximum legal length (L_{max}) resulted in a decrease in YPR (Fig. 4). YPR decreased from approximately 55 to 5 g ind⁻¹ when L_{max} was changed from unregulated (>800 mm) to 400 mm. YPR increased more slowly with an increasing F at a smaller L_{max} . On the other hand, %SPR drastically increased with a decreasing L_{max} (Fig. 5) for both sexes. At F_{cur} , %SPR increased from approximately 33% (without regulation of L_{max}) to >70% when L_{max} values were >800 and 650 mm for females and males, respectively. The increase in %SPR slowed when L_{max} was further reduced. %SPR appeared unaffected by L_{max} and only decreased with F when L_{max} was <600 mm for females and <500 mm for males (Fig. 5).

3.4. Incorporation of parameter uncertainty into the per-recruit analysis

Average values of F_{max} , $F_{0.1}$, $F_{40\%}$, and $F_{50\%}$ after accounting for the uncertainty of input parameters in the per-recruit analysis were identical to estimates from the deterministic model to the third decimal place. %SPR was about 2–3% higher than that from the deterministic model when parameter uncertainty was accounted for. However, YPR_{max} , SPR_{Fcur} , and SPR_0 were about 12–35% larger than those from the deterministic model (Table 3).

F_{max} and $F_{0.1}$ had relatively small coefficients of variation (CVs, of 1–1.3%), and their distributions were nearly symmetrical. In contrast, the amount of uncertainty for $F_{40\%}$ and $F_{50\%}$ was relatively high, with CVs of 7.5–8.9%, and distributions being symmetrical or slightly skewed to the right for females. Their distributions were also flatter (platykurtic) compared to F_{max} and $F_{0.1}$ (Fig. 6a and b).

YPR_{max} , SPR_{Fcur} , and SPR_0 had higher CV values, ranging 53–111%, implying that they were more sensitive to the input parameter uncertainty than was F_{BRP} . Moreover, the distributions of YPR_{max} , SPR_{Fcur} , and SPR_0 were highly skewed with a long tail extending to the right, i.e., YPR and SPR values 2–3-times higher than the average value occasionally occurred (Fig. 7a–c). %SPR varied moderately, with CVs of 25–32%, and its distribution was symmetrical around the mean (Fig. 7d).

Probabilities of F_{cur} being larger than F_{max} were 15–20%, as the confidence level changed from values of >99.95% to <0.05% (Fig. 8). The probability of F_{cur} being larger than $F_{0.1}$ was very high (58–66%). Probabilities were relatively high for $F_{40\%}$ (50.6–93.3% for females and 26.3–82.3% for males) and $F_{50\%}$ (84.7–99.1% for females and 73.2–96.7% for males) (Fig. 8).

4. Discussion

Knowledge of the status and exploitation level of *A. japonica* is limited compared to that for other well-studied eel species (e.g., *A. anguilla*, *A. rostrata*, *A. australis*, and *A. dieffenbachii*). Collaboration

Fig. 6. Distributions of (a) $F_{\max}$, (b) $F_{0.1}$, (c) $F_{40\%}$, and (d) $F_{50\%}$ (yr^{-1}), from 5000 Monte Carlo replicates. Sexes were pooled to calculate $F_{\max}$ and $F_{0.1}$ (gray solid line), and separated when calculating $F_{40\%}$ and $F_{50\%}$. The black solid and dotted lines in this figure and Fig. 7 indicate females and males, respectively.

among different countries and integration of data from different regions are required to assess a widely distributed species (as in the case for *A. anguilla*; Dekker, 2003a). However, eel exploitation is usually evaluated at smaller scales due to a lack of integrated data at broad geographic scales. The International Council for the Exploitation of the Sea (ICES) suggests applying practical management actions within catchments (a “management stock”, ICES, 2003). Although undertaken on a smaller scale, local-scale studies are the foundation of larger-scale studies (e.g., Dekker, 1999, 2003b), and these have been widely conducted for other anguillid species (e.g., De Leo and Gatto, 1995; Bevacqua et al., 2007 for *A. anguilla*; Hoyle and Jellyman, 2002; Chisnall et al., 2003 for *A. australis* and *A. dieffenbachii*; and Robitaille et al., 2003; Weeder and Uphoff, 2009 for *A. rostrata*).

This study showed that this local stock is nearly fully exploited, and the contribution of the SPR from this local stock to the total Japanese eel stock is below minimal thresholds under current exploitation pressures. Moreover, YPR-related F_{BRP} ($F_{\max}$ and $F_{0.1}$) values were higher than SPR-related F_{BRP} ($F_{40\%}$ and $F_{50\%}$) values for both sexes, which means that optimizing the local YPR may not result in a sustainable fishery with a sufficient SPR. As a consequence, a conflict may exist between global restrictions on maintaining the SPR and local management objectives (Dekker, 2008).

The exploitation of yellow and silver eels should be regulated to achieve a sufficient level of spawning biomass-per-recruit. Restricting F is perhaps the most direct way that a 42% reduction in F_{cur} can produce an F of $<F_{50\%}$. However, it would also reduce the YPR by

Table 3

Monte Carlo-based mean, coefficient of variation (CV, %), and 95% confidence intervals (CIs) of current fishing mortality (F_{cur} , yr^{-1}), the biological reference points ($F_{\max}$, $F_{0.1}$, $F_{40\%}$ and $F_{50\%}$), and the key management quantities ($\text{YPR}_{\max}$ (g ind^{-1}), SPR_{cur} , SPR_0 (g ind^{-1}) and %SPR (%)) for the Japanese eel fishery in the lower reaches of the Kao-Ping River in southern Taiwan. Sexes were pooled for F_{cur} , $F_{\max}$, $F_{0.1}$, and $\text{YPR}_{\max}$.

	Female			Male		
	Mean	CV	95% CI	Mean	CV	95% CI
F_{cur}	0.120	27.1	0.067–0.196			
$F_{\max}$	0.165	1.3	0.161–0.169			
$F_{0.1}$	0.115	1.0	0.112–0.117			
$F_{40\%}$	0.094	8.9	0.079–0.110	0.114	7.9	0.098–0.131
$F_{50\%}$	0.070	8.5	0.059–0.082	0.085	7.5	0.073–0.097
$\text{YPR}_{\max}$	70.8	53.1	22.6–161.8			
SPR_{cur}	408.2	111.2	12.8–1632.2	291.1	85.9	49.2–2194.0
SPR_0	1178.4	93.1	63.4–3815.1	699.8	96.7	13.4–1041.9
%SPR	32.0	31.5	14.0–52.4	39.3	25.3	21.1–59.1

Fig. 7. Distributions of (a) $YPR_{\max}$ (g ind^{-1}), (b) $SPR_{F_{\text{cur}}}$ (kg ind^{-1}), (c) SPR_0 (kg ind^{-1}), and (d) $\%SPR$ (%) from 5000 Monte Carlo replicates. Sexes were pooled when calculating $YPR_{\max}$ (gray solid line), and separated when calculating $SPR_{F_{\text{cur}}}$, SPR_0 and $\%SPR$ (%).

approximately 83%. Implementing minimum ($L_{\min}$) and maximum ($L_{\max}$) legal lengths is likely to be effective alternatives, because $L_{\min}$ is able to enhance both the YPR and $\%SPR$ (e.g., Goodyear, 1993; King, 2007), and $L_{\max}$ has the potential to effectively protect $\%SPR$ (Hoyle and Jellyman, 2002). The YPR was close to the maximum at an $L_{\min}$ of 500 mm under F_{cur} , and $\%SPR$ increased to >50% for females and >60% for males (Figs. 2 and 3). However, selectively harvesting large individuals with an $L_{\min}$ may result in an age-truncated and juvenescent stock with unstable dynamics (Anderson et al., 2008). Setting a maximum legal length ($L_{\max}$) might be a better practice to stabilize the stock than setting an $L_{\min}$ because of the reduced fishing pressure on large individuals. However, YPR declined considerably with a low $L_{\max}$. If maximum legal lengths of 850 mm for females and around 680 mm for males were implemented, a sufficient level of $\%SPR$ (>50%) would be expected, with a slight reduction of 12.5% in the YPR under F_{cur} (Figs. 4 and 5).

Since eels of different sexes cannot be harvested separately and stocks of male silver eels can be enhanced by stocking cultured eels in rivers (Lin et al., 2010b), we suggest setting a management goal with regard to female spawning biomass for maintaining future recruitment. In addition to restrictions on F and minimum and maximum legal sizes, other management strategies such as limiting or banning eel fishing in winter, when small fish are recruited to the fishing ground, were also suggested by Lin and Tzeng (2008).

The uncertainty of input parameters introduces additional variations into the estimation of F_{BRP} (Chen and Wilson, 2002). The considerable uncertainty of F_{BRP} from the SPR analysis was possibly due to variations in the parameters of the maturation curves. Furthermore, $F_{40\%}$ had a slightly higher CV than $F_{50\%}$ in this study, which is in accordance with Chang et al. (2009) where $F_{10\%}$ had the highest CV, followed by $F_{20\%}$, $F_{30\%}$, and $F_{40\%}$ for the fishery of the

pronghorn spiny lobster (*Panulirus penicillatus*). Therefore, variation in $F_{5\%}$ (i.e., the fishing mortality rate corresponding to 5% of the spawning stock biomass-per-recruit at the unfished level), possibly increases with a decrease in S , at least for values of S of 10–50.

This study suggested that the uncertainty in parameter estimation might not bias estimates of F_{BRP} , because mean values of F_{BRP} were nearly the same without this uncertainty (Tables 2 and 3). The symmetrical distributions in Fig. 6 further indicated that this uncertainty introduced only random deviations around the mean and had little influence on their mean values. Conversely, the precision and accuracy of $YPR_{\max}$, SPR_0 , and $SPR_{F_{\text{cur}}}$ appeared to be greatly influenced by this uncertainty, as indicated by different mean values with and without including parameter uncertainty, and highly skewed distributions. These key YPR and SPR values can be used to calculate expected yields (i.e., acceptable biological catch) and spawning biomass, with and without exploitation, by multiplying by the mean recruitment and then entering these values into other assessment models (Sissenwine and Shepherd, 1987; Clark, 2002). Therefore, these assessment models would be also be sensitive to the uncertainty in the parameter estimates.

Because the appropriate level of $\%SPR$ is still unclear and has not been examined for the Japanese eel, $F_{40\%}$ and $F_{50\%}$ were arbitrarily applied based on theoretical considerations given the variability of recruitment and a lack of knowledge of the stock-recruitment relationships (Clark, 1993, 2002; Gabriel and Mace, 1999), and values from other eel species. A 40% escapement of adult silver eels of *A. anguilla* from each river basin with respect to the undisturbed level was decided by the European Commission (CEC, 2006). A $\%SPR$ of 50% was suggested by Hoyle and Jellyman (2002) given the catadromous life histories of *A. dieffenbachii* and *A. australis*. An even more-conservative level of >60% of silver eel escapement was

Fig. 8. (a) Probabilities of the current fishing mortality (F_{cur}) being higher than F_{max} (black) and $F_{0.1}$ (gray), and (b) probabilities of F_{cur} being higher than $F_{40\%}$ (black) and $F_{50\%}$ (gray) for females (solid line) and males (broken line) at the given confidence levels. Confidence levels ranged from <0.05% to >99.95%.

required to permit the possible long-term (60–140-year) recovery of *A. anguilla* (ICES, 2006). It is possible that a limit of 40% SPR would still be insufficient for the declining Japanese eel stock (Dekker, 2003c). Therefore, studies examining the minimum level of %SPR and other management applications are necessary.

There are several caveats related to this study. First, only the uncertainty in the estimation of parameters was quantified and incorporated into the per-recruit analysis. However, other sources of errors (e.g., stochastic variation in parameters, Quinn and Deriso, 1999) may also have biased estimates of F_{BRP} . Thus, the uncertainty of the F_{BRP} and key YPR and SPR values for the Japanese eel are probably greater than estimated. Second, this study was restricted to the post-elver stage. Exploitation of yellow and silver eels was evaluated under the assumption that the recruitment (elvers) had already been fished by the elver fishery. This short fishing period (4–10 days) may result in losses of 44–75% of the initial immigrating population (Tzeng, 1984). The additional fishing mortality of elvers leads to underestimated mortality during the early part of life, and then underestimates SPR_0 and overestimates %SBR. Third, applying conservative levels of %SPR may conflict with local exploitation objectives (i.e., optimizing the YPR).

Restrictions on fisheries alone may be insufficient to ensure sustainable exploitation. Measures aimed at other impacts on habitat quality, quantity, and accessibility of Japanese eels will also be required (ICES, 2006). Although the Kao-Ping River is the largest river supporting the commercial yellow and silver eel fisheries, it is subject to both anthropogenic (e.g., sewage discharge and dams) and natural disturbances (e.g., typhoon Morakot in August 2009). Investigations of these effects on eels and habitat are also needed.

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Appendix A.

Definition of symbols used in yield- and spawner-biomass per recruit:

a, b :	parameters in a allometric weight–length relationship: $W = aL^b$.
F :	instantaneous fishing mortality rate (yr^{-1}).
K :	Brody growth coefficient in von Bertalanffy growth function (yr^{-1}).
$N(t)$:	the population size at time t (number of fish).
L_c :	length at first capture (mm).
L_∞ :	asymptotic length in von Bertalanffy growth function (mm).
M :	instantaneous natural mortality rate (yr^{-1}).
$S(t)$:	the proportion of silver eels at time t (%). It is assumed to change with total length of the eels and follow a logistic curve: $S(u) = \frac{1}{1 + e^{[\beta_0 + \beta_1 L_\infty (1 - e^{-K(u-t_0)})]}}$.
t_0 :	the hypothetical age when body size is zero (yr).
t_c :	the catch; the age at first capture.
t_r :	the age at recruitment (yr).
t_{max} :	the maximum age.
$W(t)$:	eel weight at time t (g).
β_0, β_1 :	maturation parameters in the logistic maturation curve.

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