

## **Supplementary material**

### **Appendix A. Standardisation of catch-rate indices**

Catch-rate indices are usually assumed to be linearly proportional to abundance and are included in stock assessments under the assumption that they are relative indices of abundance. The simplest way to obtain catch-rate indices is to divide the total annual catch by the total annual effort (so-called nominal CPUE). However, trends in nominal CPUE often differ from those in abundance because of changes over time, for example, fishing gear, location, season. Therefore, standardisation of catch and effort data (Maunder and Punt 2004) is used to eliminate as many of these effects as is possible. Nominal catch-rates are standardised in this paper using a two-stage generalised linear modelling approach, i.e. the delta method. First, a generalised linear model with a binomial response is used to analyse the data on presence or absence of blue marlin (i.e. P/A model) to determine the probability of catching blue marlin as a function of various covariates. A CPUE model is then used to model the catch rate given that it is positive, under the assumption that the errors are log-normally distributed. The CPUE model includes two-way interactions among the main effects, except for year (Maunder and Punt 2004), because there is substantial seasonal variation in the catch-rates of blue marlin and because the operation type of longline fisheries is known to change over time (Ward and Hindmarsh 2007). The model used to standardise the catch and effort data divides the dataset into two in 1975 and 1995 for the Japanese and Taiwanese longline fisheries respectively, when information on operating type (i.e. hooks per basket) became available.

### **Appendix B. Population dynamics model**

## Basic population dynamics

The population dynamics of blue marlin are assumed to be governed by an age-, sex- and region-structured model:

$$N_{t+1,a}^{s,A} = \begin{cases} N_{t+1,0}^{s,A} & \text{if } a = 0 \\ \tilde{N}_{t,a-1}^{s,A} & \text{if } 0 < a < \lambda, \text{ (B.1)} \\ \tilde{N}_{t,\lambda-1}^{s,A} + \tilde{N}_{t,\lambda}^{s,A} & \text{if } a = \lambda \end{cases}$$

where  $N_{t,a}^{s,A}$  is the number of fish of age  $a$  and sex  $s$  in region  $A$  at the start of year  $t$ ;

$\tilde{N}_{t,a}^{s,A}$  is the number of fish of age  $a$  and sex  $s$  in region  $A$  at the end of year  $t$ ; and

$\lambda$  is the maximum age considered (treated as a plus group).

The year is divided into six time-steps (bimonthly) to capture movement dynamics as well as natural and fishing mortality. Natural mortality is assumed to occur continuously throughout each bimonthly time-step whereas fishery mortality is assumed to occur instantaneously in the middle of each time-step before movement.

The number of fish of age  $a$  and sex  $s$  in region  $A$  at the start of bimonth  $m + 1$  of year  $t$ ,  $\bar{N}_{t,m+1,a}^{s,A}$ , is therefore calculated using the equation:

$$\bar{N}_{t,m+1,a}^{s,A} = X_m^{A,A} \left( \bar{N}_{t,m,a}^{s,A} e^{-M \Delta t/2} - C_{t,m,a}^{s,A} \right) e^{-M \Delta t/2} + \sum_{A' \neq A} X_m^{A,A'} \left( \bar{N}_{t,m,a}^{s,A'} e^{-M \Delta t/2} - C_{t,m,a}^{s,A'} \right) e^{-M \Delta t/2},$$

$$\bar{N}_{t,1,a}^{s,A} = N_{t,a}^{s,A} \quad \text{and} \quad \tilde{N}_{t,a}^{s,A} = \bar{N}_{t,7,a}^{s,A}, \text{ (B.2)}$$

where  $X_m^{A,A'}$  is the probability that a fish in region  $A'$  at the end of bimonth  $m$  moves

to region  $A$  at the start of bimonth  $m + 1$  given that it survived bimonth  $m$  ( $X_m^{A,A}$  is

the probability that a fish stays in region  $A$ );

$M$  is the annual instantaneous rate of natural mortality;

$\Delta t$  is the length of each bimonthly time-step (taken to 1/6 of a year);

$C_{t,m,a}^{s,A}$  is the catch, in number, of fish of age  $a$  and sex  $s$  from region  $A$  during bimonth

$m$  of year  $t$ :

$$C_{t,m,a}^{s,A} = \sum_f C_{t,m,a}^{s,A,f}, \quad (\text{B.3})$$

$C_{t,m,a}^{s,A,f}$  is the catch, in number, of fish of age  $a$  and sex  $s$  from region  $A$  by fleet  $f$  during bimonth  $m$  of year  $t$ .

### Catches

The catch in number of fish of age  $a$  and sex  $s$  by fleet  $f$  in region  $A$  during bimonth  $m$  of year  $t$  is calculated using the equation:

$$C_{t,m,a}^{s,A,f} = F_{t,m,a}^{s,A,f} \left( \bar{N}_{t,m,a}^{s,A} e^{-M \Delta t / 2} \right), \quad (\text{B.4})$$

where  $F_{t,m,a}^{s,A,f}$  is the exploitation rate on fish of age  $a$  and sex  $s$  by fleet  $f$  in the region  $A$  during year  $t$ :

$$F_{t,m,a}^{s,A,f} = s_a^{s,f} \cdot F_{t,m}^{A,f}, \quad (\text{B.5})$$

$s_a^{s,f}$  is the selectivity for fleet  $f$  on fish of age  $a$  and sex  $s$ ;

$F_{t,m}^{A,f}$  is the exploitation rate on fully-selected animals by fleet  $f$  in region  $A$  during bimonth  $m$  of year  $t$ :

$$F_{t,m}^{A,f} = \frac{C_{t,m,obs}^{A,f}}{\sum_a \sum_s s_a^{s,f} \left( \bar{N}_{t,m,a}^{s,A} e^{-M \Delta t / 2} \right)}, \quad (\text{B.6})$$

$C_{t,m,obs}^{A,f}$  is the observed catch in number from region  $A$  by fleet  $f$  during bimonth  $m$  of year  $t$ .

### Growth

The mean weight of an animal of age  $a$  and sex  $s$  is given by:

$$w_a^s = \sum_{l=1}^K \Lambda_{a,l}^s \cdot A^s L_l^{B^s}, \quad (\text{B.7})$$

where  $A^s, B^s$  are the parameters of the length–weight relationship for a fish of sex  $s$ ;  $L_l$  is the mid-point of length-class  $l$ ;

$\kappa$  is the number of length-classes considered;

$\Lambda_{a,l}^s$  is the fraction of animals of age  $a$  and sex  $s$  that are in length-class  $l$ :

$$\Lambda_{a,l}^s = \int_{L_l - \Delta L}^{L_l + \Delta L} \frac{1}{\sqrt{2\pi}\sigma_a^s} \exp\left[-\frac{(L - L_a^s)^2}{2(\sigma_a^s)^2}\right] dL, \quad (\text{B.8})$$

$\Delta L$  is half the width of a length-classes (2.5 cm);

$\sigma_a^s$  is the standard deviation of the length of a fish of sex  $s$  and age  $a$ ;

$L_a^s$  is the expected length of a fish of age  $a$  and sex  $s$ :

$$L_a^s = L_\infty^s \left(1 - e^{-k^s(t-t_0^s)}\right), \quad (\text{B.9})$$

$L_\infty^s$ ,  $k^s$  and  $t_0^s$  are the parameters of the von Bertalanffy growth equation for fish of sex  $s$ .

## **Maturity**

The proportion of female fish of age  $a$  that are mature is modeled using a logistic function:

$$\phi_a = \sum_{l=1}^{\kappa} \frac{\Lambda_{a,l}^{s=\text{female}}}{1 + \exp[r_m(L_l - L_m)]}, \quad (\text{B.10})$$

where  $\phi_a$  is the fraction of females of age  $a$  that are mature;

$r_m$  is the maturity slope parameter; and

$L_m$  is the length-at-50%-maturity for females.

## **Recruitment**

Recruitment, defined as number of fish of age 0, is assumed to be related to spawning stock biomass by means of the Beverton-Holt stock-recruitment relationship, parameterised in terms of  $h$ , the steepness of the stock-recruitment relationship (Francis 1992) and  $R_0$ , the average recruitment in the absence of exploitation. The sex-ratio at age 0 is assumed to be 1:1 in the absence of evidence to the contrary.

Density-dependence is assumed to be a function of the size of the entire mature biomass, i.e.,

$$N_{t+1,0}^{s,A} = 0.5 \cdot x^A \cdot \frac{4 h R_0 S_t / S_0}{(1-h) + (5h-1) S_t / S_0} e^{v_t - \sigma_v^2 / 2}, \quad (\text{B.11})$$

where  $S_0$  is the spawning stock biomass at unfished pre-exploitation equilibrium;

$S_t$  is the spawning stock biomass at the end of year  $t$ :

$$S_t = \sum_A S_t^A, \quad (\text{B.12})$$

$S_t^A$  is the spawning stock biomass in region  $A$  at the end of year  $t$ :

$$S_t^A = \sum_a \phi_a \cdot w_a^{s=\text{female}} \cdot \tilde{N}_{t,a}^{s=\text{female},A}, \quad (\text{B.13})$$

$x^A$  is  $S_{1937}^A / S_{1937}$  (1937 is selected because the population is assumed in unfished equilibrium at the start of 1937);

$v_t$  is a normally distributed process error,  $v_t \sim N(0, \sigma_v^2)$ ; and

$\sigma_v^2$  is the assumed variance of the process error in recruitment.

### Selectivity

Selectivity-at-length is modeled using a logistic curve and is assumed to be independent of sex:

$$s_a^{s,f} = \sum_{l=1}^K \Lambda_{a,l}^s \left( 1 + \exp \left( - \ln 19 \frac{L_l - L_{50}^f}{L_{95}^f - L_{50}^f} \right) \right)^{-1}, \quad (\text{B.14})$$

Where  $L_{50}^f$  is the length-at-50%-selectivity for fleet  $f$ ; and

$L_{95}^f$  is the length-at-95%-selectivity for fleet  $f$ .

### Initial conditions

It is not possible to project the model from pre-exploitation equilibrium because of a lack of catch records before 1952. Instead, following Hobday and Punt (2001), the population is assumed to have been in unfished equilibrium in 1937 (calculated by

projecting the model forward for 10 years, i.e. 1927-36, from arbitrary starting conditions) after which a constant exploitation rate is applied during 1937-51. The recruitments from 1937 are treated as estimable parameters. The age-structure of the population at the start of 1952 is, therefore, determined by projecting the model from 1927 to 1951.

### **Fleet-aggregated fishing intensity**

A measure of overall fishing intensity for the years during which all fleets took catches of blue marlin is calculated by dividing the total catch by a fleet-averaged exploitable number of animals in the middle of the year:

$$F_t = \frac{\sum_m \sum_A \sum_f C_{t,m,obs}^{A,f}}{\sum_A \sum_s \sum_a s_a^s (\bar{N}_{t,4,a}^{s,A})}, \quad (\text{B.15})$$

where  $F_t$  is the fleet-aggregated fishing intensity during year  $t$  and

$s_a^s$  is the fleet-aggregated selectivity for fish of age  $a$  and sex  $s$ , calculated by weighting the fleet-specific selectivity patterns by the fleet-specific exploitation rates:

$$s_a^s = \frac{\sum_f \left( \sum_A \sum_t \sum_m F_{t,m}^{A,f} \right) s_a^{s,f}}{\sum_f \sum_A \sum_t \sum_m F_{t,m}^{A,f}}, \quad (\text{B.16})$$

where the summations over year relate to the years considered in the population dynamics model.

### **Appendix C. Contributions to the objective function**

The objective function minimised<sup>1</sup> to estimate the values for the parameters of the model includes two components: the contributions from data available for assessment purposes (i.e. catch-rates, length-frequencies and relative densities across the region being assessed) and the constraints based on *a priori* assumptions for the deviations about the stock-recruitment relationship. The weighting factor ( $\rho^L$ ) assigned to the length-frequency data in the likelihood function (see Eqn C.3) is set to 0.001 because

the sample sizes for some years are very large. Giving high weight to the length-frequency data leads to poor fits to the other data sources. In contrast, the weighting factor for the proportion data ( $\rho^P$ ) is set to 1,000, to emphasize the contribution of proportion data in the likelihood function (see Eqn C.6). These weighting factors were selected by examining the model fits to the proportion and length-frequency data simultaneously.

### Catch-rate data

The indices of relative abundance based on standardised catch-rates are assumed to be log-normally distributed about the corresponding model-predictions. The contribution of these data to the negative of the log-likelihood function, ignoring constants independent of the model parameters, is:

$$-\ln L_1 = \sum_f \sum_A \sum_t \sum_m \left\{ \ln \tilde{\sigma}_1^{A,f,m} + \frac{[\ln(I_{t,m,obs}^{A,f}) - \ln(q_{T(t),m}^{A,f} \cdot B_{t,m}^{A,f})]^2}{2(\tilde{\sigma}_1^{A,f,m})^2} \right\}, \quad (C.1)$$

where  $I_{t,m,obs}^{A,f}$  is the observed catch-rate (standardised) for fleet  $f$  in region  $A$  for bimonth  $m$  of year  $t$ ;

$q_{T(t),m}^{A,f}$  is the catchability coefficient for bimonth  $m$  of year  $t$  (where year  $t$  is in period  $T$  and  $q_{T,m}^{A,f}$  might differ among periods; see below for details) for fleet  $f$  in region  $A$ ;

$B_{t,m}^{A,f}$  is the number of exploitable animals in the middle of bimonth  $m$  of year  $t$  in region  $A$  for fleet  $f$  after fishing:

$$B_{t,m}^{A,f} = \sum_s \sum_{a=1}^{\lambda} (s_a^{s,f} \cdot \bar{N}_{t,m,a}^{s,A} e^{-M \Delta t/2} - C_{t,m,a}^{s,A}), \quad (C.2)$$

$\tilde{\sigma}_1^{A,f,m}$  is the standard deviation of the fluctuations in catchability for bimonth  $m$  and fleet  $f$  in region  $A$ , assumed to be year-invariant.

Maximum likelihood estimates exist for  $\tilde{\sigma}_1^{A,f,m}$  and  $q_{T,m}^{A,f}$ .

It is often assumed that catchability is constant over time when conducting

fishery stock assessments (Ward and Hindmarsh 2007). However, the catch-effort standardisation does not account for all possible changes over time in fishing efficiency. Catchability can vary over time because fishermen adjust their vessels, gear and strategies in an attempt to maximise their catches (Hinton 2001; Kleiber *et al.* 2003), but none of these factors can be taken into account in the catch-effort standardisation owing to lack of data. Therefore, the model application considers scenarios regarding the time period  $T$  over which catchability might be constant, taking account of information on when substantial changes in fishing practices occurred (such as deep longlining operations for targeting bigeye tuna). Separate catchability coefficients are estimated for various periods of years for the Japanese longline fleets (1952–65 and 1966–2006), as well as the TWSW and TWSE fleets (1966-98 and 1999-2006) to account for changes over time in fishing practices, whereas catchability is assumed to be year-invariant for the TWNW and TWNE fleets as catch-rate data are only available for these fleets for 1995–2006.

### **Length-frequency data**

Sex-specific length-frequency data are available and expressed as sex  $s = 1$  for females and  $s = 2$  for males. The sex-aggregated length-frequency data are denoted sex  $s = 0$ . The length-frequency data (i.e. the fraction of fish caught by length-class) are assumed to be multinomially distributed and the contribution of the length-frequency data (ignoring constants independent of model parameters) to the negative of the logarithm of the likelihood function is:

$$-\ln L_2 = \rho^L \sum_f \sum_A \sum_s \sum_t n_t^{s,A,f} \sum_l P_{t,l,obs}^{s,A,f} \cdot \ln \left( P_{t,l}^{s,A,f} / P_{t,l,obs}^{s,A,f} \right), \quad (C.3)$$

where  $P_{t,l,obs}^{s,A,f}$  is the observed fraction that fish of sex  $s$  in length-class  $l$  made up of the catch (in numbers) by fleet  $f$  in region  $A$  during year  $t$ ;

$P_{t,l}^{s,A,f}$  is the model-prediction of the fraction that fish of sex  $s$  in length-class  $l$  made



up of the catch (in numbers) by fleet  $f$  in region  $A$  during year  $t$ :

$$P_{t,l}^{s,A,f} = \frac{\sum_m C_{t,m,l}^{s,A,f}}{\sum_m \sum_{l'} C_{t,m,l'}^{s,A,f}}, \quad (\text{C.4})$$

$C_{t,m,l}^{s,A,f}$  is the model-estimate of the catch (in numbers) of fish of sex  $s$  in length-class  $l$  by fleet  $f$  in region  $A$  during bimonth  $m$  of year  $t$ :

$$C_{t,m,l}^{s,A,f} = \begin{cases} \sum_{a=1}^{\lambda} \Lambda_{a,l}^s \cdot C_{t,m,a}^{s,A,f} & \text{if } s = 1 / 2 \\ \sum_s \sum_{a=1}^{\lambda} \Lambda_{a,l}^s \cdot C_{t,m,a}^{s,A,f} & \text{otherwise} \end{cases}, \quad (\text{C.5})$$

$\rho^L$  is the weighting factor assigned to the length-frequency data; and

$n_t^{s,A,f}$  is the effective sample size for the length-frequency data for sex  $s$ , fleet  $f$ , region  $A$  and year  $t$ .

### Habitat indices of relative density

Given that standardised catch-rates could indicate relative abundance spatially, the relative densities of blue marlin abundance predicted from the habitat preference model are included in the likelihood function under the assumption that the observed proportions of the population in each region are multinomially distributed about the corresponding model predictions. Ignoring constants independent of the model parameters, the contribution of the relative densities to the negative of the logarithm of the likelihood function is:

$$-\ln L_3 = \rho^P \sum_t \sum_m \sum_A p_{t,m,\text{obs}}^A \cdot \ln(p_{t,m}^A / p_{t,m,\text{obs}}^A), \quad (\text{C.6})$$

where  $\rho^P$  is the weighting factor assigned to the data on the split of the population by region;

$p_{t,m}^A$  is the model-estimate of the proportion of the population in region  $A$  at the start of bimonth  $m$  of year  $t$  (in number) based on the Japanese longline fleets (denoted by  $f = 1$ ; the Japanese fleets were selected to define the selected component of the

population because they operated consistently over time and took the bulk of the catch of blue marlin in the Pacific Ocean):

$$p_{t,m}^A = \frac{\sum_s \sum_a S_a^{s,f=1} \cdot \bar{N}_{t,m,a}^{s,A}}{\sum_A \sum_s \sum_a S_a^{s,f=1} \cdot \bar{N}_{t,m,a}^{s,A}}, \quad (\text{C.7})$$

$p_{t,m,\text{obs}}^A$  is the observed proportion of the population in region  $A$  at the start of bimonth  $m$  of year  $t$ .

### **Constraint contribution to the objective function**

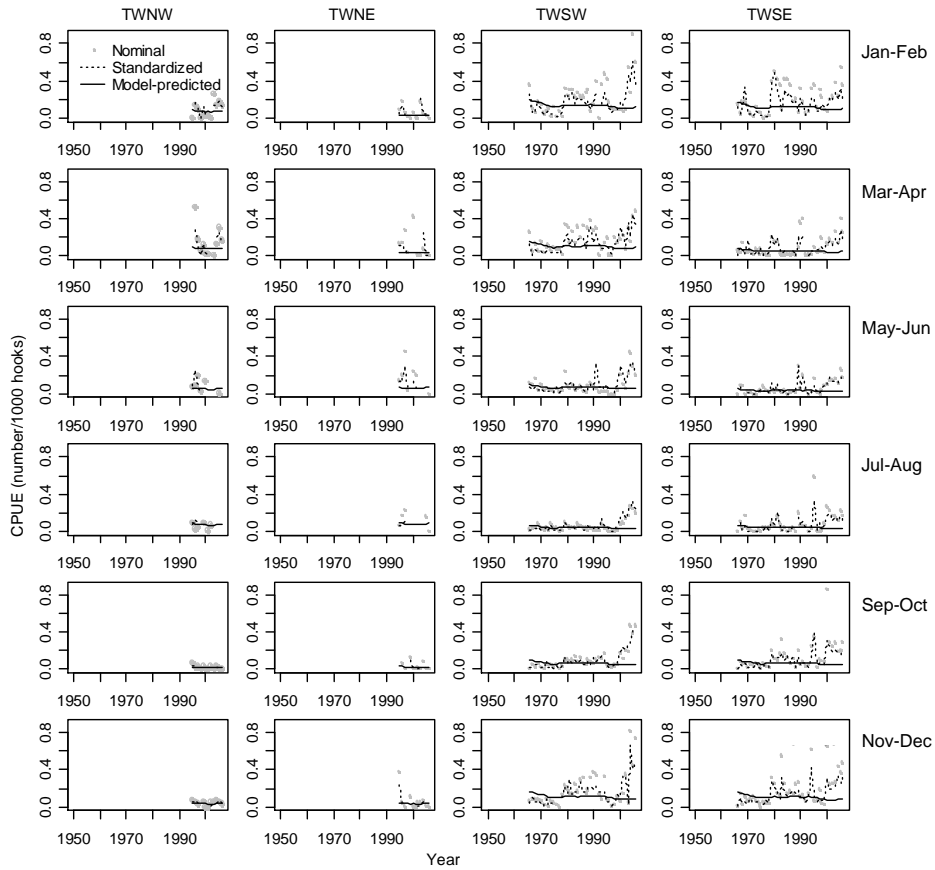
A constraint is placed on the deviations about the stock-recruitment relationship for entire period considered in the population dynamics model (1937–2006):

$$\frac{1}{2\sigma_v^2} \sum_t v_t^2. \quad (\text{C.8})$$

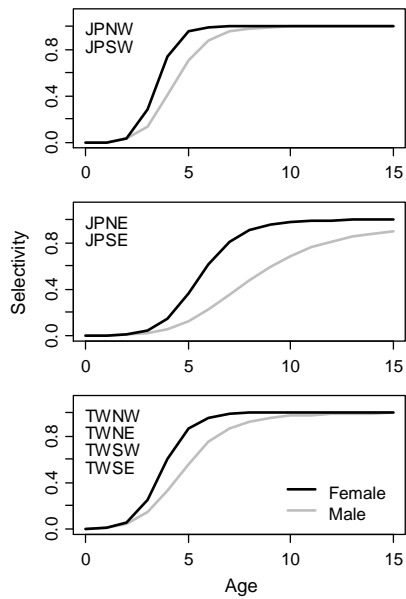
**Table A1. The values assumed for the parameters of the relationships between length and weight, maturity and age and length and age and for the standard deviation of the length-at-age**

Source: Sun *et al.* (2009), Dai (2002).

Parameter	Female	Male
Length-at-50%-maturity, $L_m$ (cm)	175.16	–
Maturity slope, $r_m$	–0.125	–
Length-weight, $A$	$1.43 \times 10^{-5}$	$1.12 \times 10^{-5}$
Length-weight, $B$	3.00	3.03
Asymptotic length, $L_\infty$ (cm)	312.5	232.8
Growth parameter, $K$ (yr <sup>-1</sup> )	0.111	0.131
Age-at-zero-length, $t_0$ (yr)	–2.42	–3.58
Standard deviation of length-at-age, $\sigma_a$		
Age 1	7.75	4.80
Age 2	7.14	4.61
Age 3	6.63	4.45
Age 4	6.21	4.31
Age 5	5.85	4.20
Age 6	5.55	4.10
Age 7	5.29	4.01
Age 8	5.07	3.94
Age 9	4.89	3.88
Age 10+	4.72	3.88



**Fig. A1.** Nominal, standardised and model-predicted catch-rates for the four Taiwanese longline fleets for 1966–2006.



**Fig. A2.** Estimated age-specific selectivity ogives for the eight fleets.

## References

- Hobday, D., and Punt, A. E. (2001). Size-structured population modelling and risk assessment of the Victorian southern rock lobster, *Jasus edwardsii*, fishery. *Marine and Freshwater Research* **52**, 1495–1507. doi:10.1071/MF01050
- Maunder, M. N., and Punt, A. E. (2004). Standardizing catch and effort data: a review of recent approaches. *Fisheries Research* **70**, 141–159. doi:10.1016/j.fishres.2004.08.002

<sup>1</sup>Using AD Model Builder (ver. 9.1). Available at <http://www.admb-project.org/> (accessed 1 September 2011).