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Supplementary Material

The population model

Input data

River discharge. All discharge data were supplied by the Queensland Department of Environment and Resource Management (Water Assessment Group 2009). River discharge represented the total monthly volume of water flowing into the Fitzroy River estuary after accounting for the reductions caused by upstream dams and abstraction for agricultural and urban use. Discharge data were modelled using a Sacramento rainfall-runoff model (Simons *et al.* 1996) calibrated with long-term (i.e., 100yr) historic rainfall, evaporation and gauged river flow. The baseline discharge for model comparisons represented the historical observed discharge to the Fitzroy River estuary and included actual levels of water abstraction (Robins *et al.* 2005). Baseline discharge for the Fitzroy River estuary was calculated as gauged streamflow at the most downstream gauging station (i.e., 'The Gap' 142.1 km adopted middle thread distance), minus seasonal extractive uses estimated by Queensland Department of Science, Information Technology, Innovation and the Arts (DSITIA) and Fitzroy River Water.

DSITIA also supplied the hypothetical river discharge based on the outputs of three Global Circulation Models: MIUB_echo_g_SRES AS used for the 10th percentile climate change scenario (i.e. LCCWet = Latent + Climate Change Wet); IAP_FGOALS1_0_g_SRES A1B used for the 50th percentile climate change scenario (i.e. LCCMed = Latent + Climate Change Median); and UKMO_HADGEM1 SRES A2 used for the 90th percentile climate change scenario (i.e. LCCDry = Latent + Climate Change Dry). The climate change scenarios for river discharge were based on exceedences i.e. the 10th percentile case is where the flow is exceeded 10% of the time (i.e. the wetter case), while the 90th percentile case is where the flow is exceeded 90% of the time (i.e. the drier case). Flow scenarios that included climate change were based on the historical flow time-series modified by the parameter change percentages to rainfall and potential evaporation in the central Queensland region under SRES emissions scenario A1FI for the 2050 projection period (QCCCE 2009). Outputs of this climate model most closely follow current trends in emissions and assume a high-reliance on fossil fuels. Full details on the generation of river discharges under climate change can be found in Water Assessment Group (2009).

*Commercial barramundi harvest***.** Regional commercial harvest data were obtained from: (i) the Queensland Fish Board (Rockhampton, Yeppoon and Rosslyn Bay regional depots) between 1945 and 1980; and (ii) the compulsory commercial logbook of Fisheries Queensland (spatial grids R28, R29, R30 and S29) between 1990 and 2005 (Robins *et al.* 2005). Annual harvest records from the Queensland Fish Board (QFB) were split into monthly estimates based on averaged monthly trends in barramundi landings to the Brisbane Metropolitan Fish Market between 1937 and 1960. Commercial logbook barramundi catch rates from 1990 to 2005 were standardised using a general linear model (Genstat 2008). Forward stepwise regression was used to select model explanatory terms. All continuous data were natural logarithm transformed to normalise variances. The model response variable was the log of monthly harvest (kg) from each vessel. Explanatory model terms were the interaction of fishing year and month, and the main effects of individual vessel operations, log gill-net length, log number of days fished per vessel per month, and the log harvest of other species per vessel per month. All terms in the catch rate standardisation were significant ($P < 0.01$) except log gill-net length ($P = 0.286$) and the harvest of other species per vessel per month ($P = 0.107$). The standardised catch rate (kg/month) was predicted and back transformed from the general linear model, with non-significant terms removed. The regression model accounted for 70.6% of variance in monthly barramundi catch (residual mean square = 0.546, d.f. = 2795). Analysis of residuals supported the use of the final model structure and normal statistical distribution. A time gap in the total harvest records existed between when the QFB data and the compulsory commercial logbook. Estimates of monthly harvest between 1981 and 1989 were interpolated using the von Mises distribution (Mardia and Jupp 2000) with a seasonal catch trend.

Observed age and length frequencies. Frequencies of barramundi catch-at-length and catch-at-age were collected from the commercial net fishery of the Fitzroy River region between October 2000 and February 2005. See Halliday *et al.* (2011) for details.

Recruitment

Monthly recruitment was the product of the within-fishing-year recruitment pattern (Φ_m) and the total annual number of fish recruiting (R_y). Recruitment ($\hat{R}_y$) in year y was estimated from a Beverton-Holt spawning stock-recruitment relationship:

$$\hat{R}_y = \frac{E_{y-1}}{\alpha + \beta E_{y-1}} \text{ ; where } \begin{array}{l} \alpha = \frac{E_0(1-h)}{4h\hat{R}_0} \\ \beta = \frac{5h-1}{4h\hat{R}_0} \end{array} \quad \text{(A1)}$$

In equation A1, E_o was the initial virgin spawning stock size and h was the steepness of the stock recruitment curve; defined as the proportion of the virgin recruitment produced by 20% of the virgin spawning stock. Virgin recruitment $\hat{R}_0$ was estimated in the calibration stage of modelling by MCMC (see main text). The model was tuned and projected using values of 0.5, 0.7 and 0.9 for h to provide an assessment of the impacts of uncertainty in the spawner-recruit relationship, with 0.7 considered the base-case (see main text). Recruitment variation was modelled by incorporating environmental variability based on river discharge to the estuary and log-normal error (Mangel *et al.* 2010). This was achieved by adding extra model terms into the estimated yearly recruitment ($\hat{R}_y$), see equation 1 in the main text.

Spawning stock size

Spawning stock size in terms of number of eggs (E_y), was the sum of the product of the number of mature females and the fecundity index across length-classes:

$$E_y = \sum_{m=1}^{12} \sum_{l=L_{\min}}^{L_{\max}} \sum_{a=A_{\min}}^{A_{\max}} Sp_m N_{l,a,m} sex_l mat_l \, fec_l \quad \text{(A2)}$$

where m = month of the year (1:12, July to June respectively); l =length-class, L_{min} (300 mm) and $L_{\max}$ (1830 mm) were the minimum and maximum length-classes; a = age-class, A_{min} (12 months) and A_{max} (384 months) were the first and last age-classes, Sp_m was the monthly spawning pattern in month m, with 80% occurring between October and January (i.e., 20% per m), 10% in each of September and February, and the remaining months contributing no effective egg production (Dunstan 1959); $N_{l,a,m}$

was the number of fish of age-class *a* in length-class *l* for month *m* (see equation A13); sex_l was sex-transition matrix for barramundi changing sex from male to female (see equation A12); mat_l was the seasonal proportion of individuals mature in length-class *l*, based on a logistic regression fitted to data reported in Davis (1982, Table 1):

$$\log\left(\frac{P_l}{1-P_l}\right) = \beta_0 + \beta_1 l + \varepsilon \qquad \text{(A3)}$$

where, P_l was the proportion of mature fish in length-class *l*, β_0 = -13.19 (±1.833 s.e.) and β_1 = 0.02 (±0.003 s.e.); and fec_l = $0.3089e^{0.0035l}$ was the fecundity (number of eggs x10^6) of fish in length-class *l* (Davis 1984).

Mortality

Fishing mortality (U_m) was calculated in terms of harvest rate:

$$U_m = \frac{catch_m}{B_m} \tag{A4}$$

where $catch_m$ was the observed total harvest (kg) per month and B_m was the monthly exploitable biomass (kg). In the projection phase, fishing mortality was expressed by monthly instantaneous fishing mortality (F_m) and was based on the median harvest rate per month in the last four years of the calibration stage ($U_{med:\ 2001–2005}$) with variation based on a log-normal distribution and a standard deviation equivalent to that of the catchability coefficient q_2 (see equation A15) for each replicate:

$$F_m = -\log\left(1 - U_{med:2001\text{-}2005}\right) S_{l,gm} D_l \tag{A5}$$

where $S_{l,gm}$ = net selectivity of fish in length-class l for gill-net mesh size gm (equations A8 and A9); D_l = discard mortality of fish in length-class l, which was 10% for fish <580 mm (Grace *et al.* 2008) and 10% for fish >1200 mm (I. Halliday, personal observation).

Biomass

Exploitable biomass (i.e., biomass vulnerable to fishing) was based on fish >12 months-old and <33-years-old; and between 300 and 1830 mm in total length. Exploitable biomass was calculated as:

$$B_m = \sum_{l=L_{\min}}^{L_{\max}} \sum_{a=A_{\min}}^{A_{\max}} N_{l,a,m} W_l S_{l,gm} \tag{A6}$$

The weight of a fish in length-class l was (Halliday unpublished data):

$$W_l = 2e\text{-}08\ l^{\,2.9526} \tag{A7}$$

and the gill net selectivity for a fish in length-class l was (Hyland 2007):

$$S_{l,gm} = \exp\left[\frac{-(l-k_1\cdot gm_{6"})^2}{2k_2\cdot gm_{6"}^2}\right] \text{ for February to June} \tag{A8}$$

and

$$S_{l,gm} = \begin{cases} \exp\left[\frac{-(l-k_1\cdot gm_{6"})^2}{2k_2\cdot {gm_{6"}}^2}\right] & \text{for } l = L_{\min},\ldots,L_{6"\max-1} \\ 1 & \text{for } l = L_{6"\max},\ldots,L_{8"\max} \\ \exp\left[\frac{-(l-k_1\cdot gm_{8"})^2}{2k_2\cdot {gm_{8"}}^2}\right] & \text{for } l = L_{8"\max+1},\ldots,L_{\max} \end{cases} \text{ for July to October} \tag{A9}$$

where $gm_{6''}$ and $gm_{8''}$ were gill-net mesh sizes 152.4 mm and 203.2 mm respectively, k_1 and k_2 were estimated parameters (k_1 = 5.203; k_2 = 0.619) and $L_{\min}$ (300 mm) and $L_{\max}$ (1830 mm) were the minimum and maximum length-classes, and $L_{6''\max}$ and $L_{8''\max}$ were the length-classes that reached maximum selectivity for the gill-net mesh sizes 152.4 mm and 203.2 mm respectively. A selectivity of 100% was assumed for length-classes between $L_{6''\max}$ and $L_{8''\max}$.

Growth

The growth of fish older than 12 months was determined by a discharge-dependent length-class transition matrix, where $P_{l,l'}$ was the fraction of fish in length-class *l'* that grow into length-class *l* in one month (see equation 2 main text). The expected growth increment for length-class *l* was:

$$g_{l,m} = (L_\infty - l)\left(1 - e^{-K\delta_m + S(t-\delta_m) - S(t)}\right) \tag{A10}$$

where

$K,$ average expotential growth rate $= \begin{cases} k_a + k_b(\log flow - k_{cut}) & \text{if } \log flow > k_{cut} \\ k_a & \text{if } \log flow \le k_{cut} \end{cases}$

δ_m = number of days in month m;

$$S_{(t)} = \frac{CK\sin\left(2\pi(t-t_s)\right)}{2\pi} \tag{A11}$$

t = the first day of the month; t_s, the time shift for the annual cycle (Somers 1988) = 17.91;

L_∞, the asympotic length = 1830 mm; C, the magnitude of seasonal oscillation = 1.06;

k_a = 0.07; k_b = 0.01; and k_{cut} = 6.92 based on the results of Robins *et al*. (2006)

Sex transition

Barramundi is a protandrous hermaphrodite, maturing as males at three to five years and changing sex from male to female at seven to eight years. Therefore, female numbers were calculated as the product of total abundance of males by the sex-transition matrix:

$$sex_l = \frac{1}{1+\exp\left(-\ln(19)\frac{l-l_{50}}{l_{95}-l_{50}}\right)} \qquad \text{(A12)}$$

where

sex_l = proportion of female fish in length class l; l_{50}, l_{95} = the lengths at which 50% and 95% of the fish became females; l_{50} = 950 mm and l_{95} = 1010 mm, based on the results of Davis (1982).

Population abundance

The numbers of barramundi ($N_{l,a,m}$) were calculated as:

$$N_{l,a,m} = \begin{cases} R_y P_{l,a,=A_{\min}} \Phi_m & \text{for } a = A_{\min} \\ P_{l,l'} N_{l',a-1,m-1} e^{-M}(1-D_{l'} S_{l',gm} U_{m-1}) & \text{for } a = A_{\min}+1,...,A_{\max} \ \& \ y \le 2005 \\ P_{l,l'} N_{l',a-1,m-1} e^{-(M+F_m)} & \text{for } a = A_{\min}+1,...,A_{\max} \ \& \ y > 2005 \end{cases} \qquad \text{(A13)}$$

where R_y was recruitment in year y estimated from a Beverton-Holt function adjusted by anomalies in summer and spring discharge from the previous year and recruitment error for years > 2005 (equation 1 main text); $P_{l,a=A\min}$ was the fraction of fish in length-class l for an age-class a in months where A_{min} = 12, the first age-class; Φ_m was the monthly proportion of annual recruits in month m; $P_{l,l'}$ was the fraction of fish in length-class l' that grew into length-class l in one month (equation 2 main text); $N_{l',a-1}$ was the abundance of fish in length-class l' in age-class $a-1$; M was instantaneous monthly natural morality rate = 0.025 month^{-1} (Grace *et al.* 2008); A_{max} = 384 months, the oldest age-class; and y was the fishing year. Different growth transition matrices were applied for each replicate discharge sequence within scenarios according to the respective monthly discharge.

Catch

Once the time-series of exploitable biomass and number of fish were calculated, monthly catch rates were predicted:

$$\widehat{cpue_m} = q_k B_m \qquad \begin{cases} \text{for } k=1,\ 541 \le m \le 672\ (1990 \le y \le 2000) \\ \text{for } k=2,\ \text{m} \ge 673\ (y \ge 2001) \end{cases} \qquad \text{(A14)}$$

The catchability coefficient (q) was calculated as the geometric mean of the ratio of CPUE to exploitable biomass:

$$q_k = \prod_t^n \left(\frac{cpue_m}{B_m} \right)^{\frac{1}{n}} \qquad \begin{cases} \text{for } k=1,\ \text{m} = 541,...,672\ (n=132) \\ \text{for } k=2,\ \text{m} = 673,...,732\ (n=60) \end{cases} \qquad \text{(A15)}$$

Two values of q were calculated because there was a major increase in barramundi standardised catch rates after 2001 as a consequence of an investment warning by Fisheries Queensland: q_1 for 1990 to 2000; and q_2 for 2001 to 2005.

Monthly catch-at-length (equation A16) and monthly catch-at-age (equation A17) were calculated as:

$$\hat{C}_{l,m} = \sum_{a=A_{\min}}^{A_{\max}} N_{l,a,m} U_m S_{l,gm} H_l \qquad \text{(A16)}$$

And

$$\hat{C}_{a,m} = \sum_{l=L_{\min}}^{L_{\max}} N_{l,a,m} U_m S_{l,gm} H_l \qquad \text{(A17)}$$

included a retainability multiplier (H_l), which was one within the legal size range, 580 to 1200 mm, and zero outside the legal size range.

For model projections beyond 2005, monthly fish harvest was expressed as the Baranov catch equation:

$$C_m = \sum_{l=L_{\min}}^{L_{\max}} \sum_{a=A_{\min}}^{A_{\max}} \frac{F_m}{M + F_m} N_{l,a,m} H_l W_l \left(1 - e^{-(M+F_m)}\right) \qquad \text{(A18)}$$

where l was length-class, L_{min} and L_{max} the minimum and maximum length-classes (300 and 1830 mm respectively); a was monthly age-class, A_{min} and A_{max} were the first and last age-classes (12 and 384 months respectively); F_m was the instantaneous monthly fishing mortality in month m, where fishing mortality $f = -\log(1-\hat{U})$ and $\hat{U}$ = median monthly harvest rate estimated from 2001 to 2004, including the annual fishing closure between November and February; M was instantaneous monthly natural morality rate = 0.025 month^{-1} (Grace *et al.* 2008); $N_{l,a,m}$ was the number of fish of age-class a in length-class l in month m; H_l was the retainability of fish in length-class l; and W_l (equation A7) was the weight of a fish in length-class l.

Fishery indicators

Equilibrium maximum sustainable yield (MSY) was estimated by optimising the dynamics of the operating model through fishing mortality (F). Recruitment dynamics were calculated according to the respective spawner-recruitment relationship with constant monthly discharge, which was calculated as the median of observed monthly discharge for the respective discharge scenario. The equilibrium model was run over 50 years with constant monthly natural and fishing mortality pattern until the population dynamics stabilised (i.e., reached equilibrium). The product from the 50 years of fishing was the equilibrium catch measured in kilograms. Fishing effort (F) was optimised to maximise MSY. The rest of the performance measures were estimated through the population simulation.

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