



## An assessment of recreational fishery harvest policies for Murray cod in southeast Australia

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### ABSTRACT

Murray cod *Maccullochella peelii peelii* is one of the world's largest freshwater fish and supports popular fisheries in southeast Australia, but no previous modelling efforts have evaluated the effects of fisheries regulations or attempted to develop sustainable harvest policies. We compiled existing population metrics and constructed an age-structured model to evaluate the effects of minimum length limits (MLLs) and fishing mortality rates on Murray cod fisheries. The model incorporated a Beverton and Holt stock recruit curve, age-specific survivorship and vulnerability schedules, and discard (catch and release) mortality for fish caught and released. Output metrics included yield (kg), spawning potential ratio (SPR), total angler catch, total harvest, and the proportion of angler trips that would be influenced by each regulation based on recent creel survey data. The model suggested that annual exploitation ( $U$ ) should be held to less than 0.15 under the current MLL of 500 mm total length to achieve an SPR > 0.3, a target usually considered to prevent recruitment overfishing. Exploitation rates at or exceeding 0.3 would cause SPR values to drop below typical management targets unless the MLL was set at or above 700 mm. Regulations that protected Murray cod from overfishing created higher angler catches and higher catch of trophy fish, but at a cost of reducing the proportion of angler trips resulting in a harvested fish. Expressing model output on a per-angler trip basis may help fishery managers explain regulation trade offs to anglers.

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The Murray cod *Maccullochella peelii peelii* is found in the extensive Murray Darling basin of southeastern Australia. As one of the world's largest freshwater fish with maximum size exceeding 100 kg, Murray cod support popular recreational fisheries in Australian states including New South Wales, Victoria, South Australia, and Queensland. Although recreational Murray cod fisheries are regulated with a range of size limits, bag limits, and closed seasons (Lintermans et al., 2005), no previous efforts have evaluated the influence of fishing on Murray cod populations or evaluated optimal harvest strategies. We compiled available life history parameters for Murray cod and constructed an age-structured population model to evaluate the effects of harvest policies for recreational fisheries.

Murray cod has undergone a range of fisheries over the past two centuries. Commercial fisheries began as early as the mid 1800s, and records indicate that commercial catches and catch per licensed boat decreased substantially from the 1940s to the early 1980s (Rowland, 1989). The commercial fishery declined due to low harvests by the mid 1960s, and New South Wales closed commer-

cial harvest for Murray cod in 2001 (Rowland, 2005). Recreational fishing for Murray cod has been popular for decades, but the extent of recreational effort and harvest is not well documented through time. A national survey of recreational fishing estimated annual harvest of about 110,000 Murray cod in 2001 with about 375,000 fish released by anglers (Henry and Lyle, 2003). Thus, Murray cod support important recreational fisheries today, and there is a need for an assessment evaluating potential impacts of a range of harvest policies on angling quality and sustainability. We compiled existing life history (e.g., growth and mortality) and fishery parameters (minimum size limits and discard mortality) for Murray cod and incorporated these parameters into an age-structured population model to evaluate harvest policies including minimum length limits (MLL) and fishing mortality rates.

### 1. Methods

We constructed an age-structured simulation model similar to Walters and Martell (2004, chapter 3) and Allen et al. (2008). The model employed survival schedules, fecundity schedules and a Botsford formulation of a Beverton–Holt stock–recruitment function to predict equilibrium recruitment and age-specific abundance under a variety of fishing mortality rates and harvest regulation

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scenarios. Survival schedules incorporated natural, harvest and discard mortalities. Harvest was driven by a stated exploitation rate and length-based vulnerabilities which included simulated MLLs. Fecundity was specified as a function of fish weight and the collective fecundity for a given year was reduced by all mortality sources. The model included ages 1–40 and was constructed in Excel®.

Equilibrium recruitment was calculated using a Botsford modification of a Beverton–Holt stock-recruitment function (Botsford and Wickham, 1979; Botsford, 1981a,b) as described by Walters and Martell (2004). This simple formulation predicts equilibrium recruitment as a function of the fishing mortality rate. The model predicted the equilibrium age-1 recruits ( $R_{eq}$ ) of an exploited population and is summarized in Walters and Martell (2004) as

$$R_{eq} = R_0 \frac{CR - (\Phi_0/\Phi_f)}{CR - 1} \quad (1)$$

where  $R_0$  is the number of age-1 recruits of the unfished population at equilibrium and  $CR$  is the Goodyear compensation ratio (Goodyear, 1980), defined as the ratio of the recruits per spawner at very low population abundance (i.e., at the origin of the stock recruit curve) relative to the recruits per spawner in the unfished equilibrium condition. The parameter  $R_0$  is the virgin age-1 recruitment and was simply a scaling parameter that did not influence most model predictions, except for the angler catch predictions described below. The model also included the option for stochastic recruitment variability using log-normally distributed deviate with mean of 1 and error ( $\sigma_R$ ) around the equilibrium stock recruitment prediction  $R_{eq}$ .

Age-specific fecundity was estimated as a quadratic function of fish weight (Rowland, 1998):

$$f_a = \beta_0 + \beta_1 w_a + \beta_2 w_a^2 \quad (2)$$

where  $w_a$  is the mean weight-at-age,  $\beta_0$  is the  $y$ -intercept, and  $\beta_1$  and  $\beta_2$  are fecundity-weight coefficients. To account for the cumulative affects of fishing on the reproductive capacity of the population, we used the incidence functions for the unfished ( $\Phi_0$ ) and fished egg production per recruit ( $\Phi_f$ ) as per Walters and Martell (2004). These incidence functions were calculated as

$$\Phi_0 = \sum_a f_a l_a \quad (3)$$

$$\Phi_f = \sum_a f_a l_{fa} \quad (4)$$

where  $f_a$  represents age-specific fecundity, and  $l_a$  and  $l_{fa}$  are the survivorship schedules of the unfished and fished state, respectively. The value of ( $f_a$ ) was set to zero if age was less than age at maturity ( $A_{mat}$ ), resulting in a knife-edge fecundity with age relationship.

The model used survivorship curves to calculate the survivors per recruit to each age. Survivorship to age  $a$  in the absence of fishing was found as

$$l_a = S_a l_{a-1} \quad (5)$$

where  $S_a$  is the age-specific finite annual natural survival rate (i.e.,  $e^{-M}$ ). Discard mortality of fish caught and released by anglers is an important consideration in recreational fisheries where length limits can cause large numbers of fish to be released (Coggins et al., 2007). Our survivorship schedules in the fished condition incorporated natural mortality, harvest, and discard mortality as

$$l_{fa} = l_{fa-1} S_a (1 - UV'_{a-1}) (1 - (U_0 V_{a-1} - UV'_{a-1}) D) \quad (6)$$

where  $l_{fa}$  is the survivorship in fished condition,  $U$  is the finite annual exploitation rate,  $U_0$  is the finite rate of capture by anglers,  $V_a$  and  $V'_a$  are age-specific vulnerabilities to harvest and capture, and  $D$  is the discard (catch and release) mortality rate. The first

**Table 1**  
Parameters used in the simulation model.

Parameter		Value
<b>Natural mortality</b>		
$M$	Instantaneous adult natural mortality (year <sup>-1</sup> )	0.108
$S_a$	Annual natural survival	0.47–0.91
$c$	Natural mortality exponent	0.9
$TL_r$	Reference length for natural mortality (mm)	1,068
<b>Fishing mortality</b>		
$U$	Annual harvest exploitation rate	0.05–0.4
$U_0$	Annual capture rate	0.06–0.44
$D$	Discard mortality rate	0.05
<b>Vulnerability</b>		
$L_{low}$	Lower length at 50% capture vulnerability (mm)	300
$SD_{low}$	Standard deviation of 50% capture vulnerability	30
$L_{high}$	Upper length at 50% capture vulnerability (mm)	1,100
$SD_{high}$	Standard deviation of 50% capture vulnerability	110
$MLL$	Length at 50% harvest vulnerability (mm)	400–800
$SD_{MLL}$	Standard deviation of 50% harvest vulnerability	0.1 × MLL
<b>Growth</b>		
$L_\infty$	Asymptotic length (mm)	1,202
$K$	Metabolic coefficient (year <sup>-1</sup> )	0.108
$t_0$	Time at zero length (year)	0
<b>Length-weight</b>		
$a$	Length-weight coefficient (mm to grams)	0.000036
$b$	Length-weight exponent	2.91
<b>Recruitment</b>		
$R_0$	Average annual unfished recruitment	100,000
$CR$	Goodyear compensation ratio	30
$\beta_0$	Fecundity-weight intercept	-389
$\beta_1$	Fecundity-weight coefficient	5,344
$\beta_2$	Fecundity-weight coefficient	-69.5
$A_{mat}$	Age at maturity (years)	5

term  $U \times V'_{a-1}$  describes deaths due to harvest, and the last term ( $U_0 \times V_{a-1} - U \times V'_{a-1}$ ) ×  $D$  models deaths due to discard mortality for fish caught below the MLL and those that are legal to harvest but are voluntarily released by anglers. Thus, the model included deaths due to discard mortality for both fish protected from harvest and those that were voluntarily released by anglers and die due to discard mortality. Age-specific abundance ( $N_a$ ) was estimated as the product of the number of age-1 recruits ( $R_{eq}$ ) and the age-specific survivorship schedule.

The model used length specific differences in natural and fishing mortality. We estimated the annual natural survival rate  $S_a$  as per Lorenzen (2000):

$$S_a = e^{-M(TL_r/TL_a)^c} \quad (7)$$

where  $M$  is the instantaneous natural mortality rate at  $TL_r$ ,  $TL_a$  is the mean total length at age,  $TL_r$  is a reference length, and  $c$  is the allometric exponent modifying the relationship between natural mortality and length. Mean total length at age,  $L_a$ , was calculated from the von Bertalanffy growth model. Values of  $TL_r$  were set at the median age (age 20 in the model, corresponding to total length of 1068 mm total length, Table 1). We specified the proportion of fish vulnerable to capture and harvest ( $V_a$  and  $V'_a$ , respectively) using a dome-shaped double logistic model:

$$V_a = \frac{1}{(1 + e^{-(TL-L_{low})/SD_{low}})} - \frac{1}{(1 + e^{-(TL-L_{high})/SD_{high}})} \quad (8)$$

where  $V_a$  is the vulnerability schedule (either  $V_a$  or  $V'_a$ ),  $TL$  is the mean total length at age  $a$ ,  $L_{low}$  is the lower total length at 50% vulnerability to capture,  $SD_{low}$  is the standard deviation of the logistic distribution for  $L_{low}$ ,  $L_{high}$  is the upper total length at 50% vulnerability to capture, and  $SD_{high}$  is the standard deviation for  $L_{high}$ . The left term models increasing vulnerability to harvest with length, and the right term can be used to simulate declining vulnerability

with fish length, either as a harvest window or in cases where fish vulnerability to fishing may decline for large fish. Values of  $SD_{low}$  and  $SD_{high}$  specify the steepness of each side of the curve, and were set at 10% of the respective length at 50% vulnerability. When calculating harvest vulnerability ( $V'_a$ ), we substituted a minimum length limit (MLL) and standard deviation for the MLL ( $SD_{MLL}$ ) for  $L_{low}$  and  $SD_{low}$  in Eq. (8).

To evaluate the performance of various harvest regulations, we simulated a range of exploitation rates (0.05–0.4) and MLLs (400–800 mm). Model output metrics included yield (kg), total angler catch (fish harvested and released), total harvest (number of fish), the number of trophy fish (total length  $\geq 1000$  mm) in the population, and the spawning potential ratio (SPR). We used the static spawning potential ratio (SPR) to evaluate the extent to which fishing mortality can reduce reproductive output of Murray cod:

$$SPR = \frac{\Phi_f}{\Phi_0} \quad (9)$$

where  $\Phi_f$  and  $\Phi_0$  are defined in Eqs. (3) and (4). The SPR measures the lifetime fecundity per recruit for a given level of fishing mortality and is a commonly used reference to assess fisheries sustainability (Goodyear, 1993). Recruitment overfishing is generally prevented by maintaining an  $SPR \geq 0.4$  (Mace, 1994). However, target SPR values vary with stock productivity, with lower SPR required for sustaining highly productive stocks (e.g., SPR of 0.3–0.4; Clark, 2002).

We used the model to evaluate effects of varying MLLs on angler catches. All simulations began with 100,000 fish recruiting to age-1 in the unfished condition ( $R_0$ ), which resulted in model-predicted harvest that was similar to the estimated angler harvest from a recent creel survey from the middle Murray River (Brown, 2008). This stratified random creel survey was conducted in the river section from the Yarrowonga weir to the Torrumbarry weir in 2006 and 2007 (Brown, 2008). The creel survey results were used to measure the proportion of angler trips that caught 0, 1, 2, etc. Murray cod per trip, and the proportion of trips that harvested 0, 1, 2, etc. fish (i.e.,  $\geq 500$  mm) in 2006–2007. We tuned  $R_0$  in Eq. (1) so that the model produced similar harvest estimates to the creel survey from this section of the river under the current MLL (500 mm). For each alternate MLL considered in the model, we estimated the probability of capturing 0, 1, 2 fish, etc. using a Poisson probability density function:

$$P_n = \frac{e^{-\lambda} \lambda^n}{n!} \quad (10)$$

where  $P_n$  is the probability of capturing  $n$  Murray cod per-angler trip given a mean catch per-angler trip ( $\lambda$ ). We calculated  $\lambda$  for each MLL and metric by dividing the model-predicted catch by the estimated number of angler trips per year from the creel survey (196,299, 4.5-h angler trips; Brown, 2008). The model predicted the proportion of trips with Murray cod catch (i.e., all fish sizes), harvest (i.e., catch of legal-sized fish), and catch of trophy fish ( $TL \geq 1000$  mm) under each simulated MLL. The exploitation rate for Murray cod was not known, and we conducted this analysis using an assumed annual harvest exploitation rate of 0.15 as a hypothesized moderate level of fishing mortality.

Parameter estimates used in the model simulations are shown in Table 1. We specified a CR of 30 for Murray cod, which is similar to a wide range of relatively long-lived predators from meta-analyses of Myers et al. (1999) and Goodwin et al. (2006). This value suggests relatively high compensation for fishing, which is typical of long-lived predators that utilize a wide range of prey types throughout their ontogeny.

Murray cod size at 50% maturity has been estimated as 519 mm from recent surveys of Victoria Department of Primary Industries

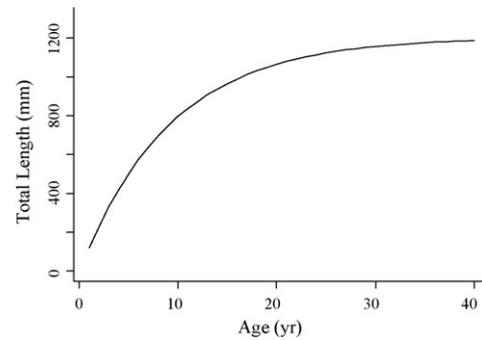


Fig. 1. Relationship between mean total length (mm) and age for all simulations. Values of the growth curve are from Anderson et al. (1992).

(VDPI) staff in the Murray basin (J. Douglas, personal communication). This value is similar to previous work from Rowland (1998), which showed that fish were about 50% mature at length groups between 500 and 550 mm. We specified the age at 50% maturity ( $A_{mat}$ ) at age 5, which corresponded to a model-predicted total length of 502 mm and a weight at 50% maturity of 2.6 kg and approximated estimates from VDPI and Rowland (1998).

The von Bertalanffy growth curve used for all simulations is shown in Fig. 1. We used growth parameters for Murray cod from Anderson et al. (1992). This curve used asymptotic length ( $L_\infty$ ) and metabolic parameter ( $K$ ) values from Anderson et al. (1992), which included a sample of 290 fish with a maximum age of 36, including fish from the middle Murray River. We fixed the time at zero length ( $t_0$ ) at zero for all simulations. The value of  $K$  was 0.108, which we used as a surrogate for the natural mortality rate ( $M$ ). Setting  $M$  equal to  $K$  provided similar estimates of  $M$  to methods based on maximum age (e.g., Hoenig, 1983; Pauly, 1980) and is frequently used in modelling efforts (Walters and Martell, 2004). We used a value of 0.9 for  $c$  in the Lorenzen natural survival curve from Eq. (7). The resulting age-specific changes in natural survival are shown in Fig. 2. To predict fish weight from length, we used estimates of the  $a$  and  $b$  parameters from Anderson et al. (1992) for the weight-length relationship (Table 1).

Discard mortality of fish released was set at 5% for all simulations. This discard mortality rate is relatively low but supported by recent estimates from VDPI researchers (J. Douglas, unpublished data). We assumed that anglers voluntarily released 15% of the fish that were legal to harvest, based on recent creel surveys in the Murray River (Brown, 2008). Thus,  $U_0$  was set as  $U_0 = U + (U \times 0.15)$  for all simulations.

The fish total length at 50% vulnerability to angling was set at 300 mm (Table 1), because fish less than 200 mm are rare in the recreational catch (Brown, 2008). However, we suspected that

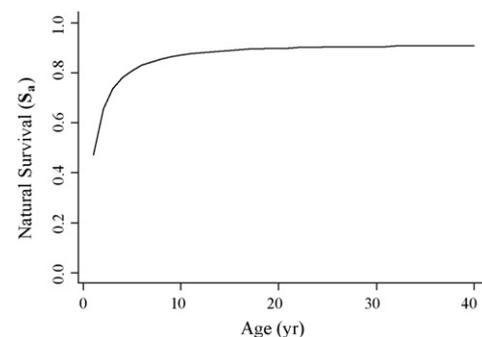


Fig. 2. Relationship between annual natural survival and age used in the population model.

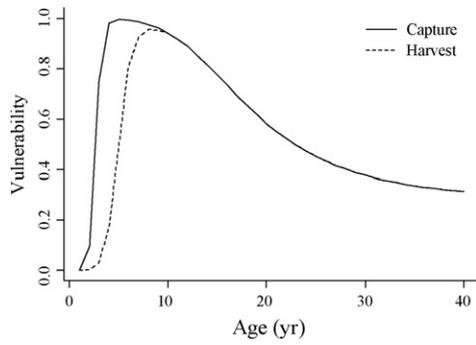


Fig. 3. Age-specific vulnerability to capture (solid line) and harvest (dashed line) under a 500-mm minimum length limit.

vulnerability to angling declined for large fish. Dome shaped vulnerability is not uncommon for recreational line fisheries, even for relatively small fish (e.g., Miranda and Dorr, 2000; Newby et al., 2000). Most Murray cod anglers use lures and natural baits that are no larger than 100–200 mm, and large-gaped fish predators readily consume prey up to 30% of their total length (Scharf et al., 2000). This would infer that a 1000-mm Murray cod would consume prey up to 300 mm, and few fishing lures used by anglers are this large. Therefore, we used a dome-shaped capture vulnerability for angling in the model (Table 1). The dome-shaped curve used for capture vulnerability and an example 500 mm MLL are shown in Fig. 3. The model predicted that fish are vulnerable to capture for 2–3 years prior to harvest under this MLL, and vulnerability to fishing declined gradually after age 10 (Fig. 3).

We conducted two types of sensitivity analyses to evaluate the response of SPR and yield to perturbations in  $M, D, L_{low}, L_{high}, L_{\infty}, K, CR, A_{mat}, TL_r,$  and  $c$ . The first analysis evaluated the elasticity of SPR and yield to relatively small changes in each parameter. Elasticity represents the proportional response of a function to a proportional change in a parameter value and is useful for estimating the relative influence of parameters on a model when the parameters are measured on different scales (Caswell, 2002). We calculated elasticity as the proportional change in SPR and yield resulting from a 5% increase in each parameter value. Elasticity analysis shows the relative influence of parameters in the neighbourhood of their baseline value but does not reveal the influence of large errors in parameters. Thus, the second sensitivity analysis evaluated how large amounts of uncertainty in model parameters would influence our predictions by plotting SPR and yield across a wide range of values for each parameter.

## 2. Results

The model-predicted SPR values were less than 0.3 at exploitation rates exceeding 0.3 when the MLL was less than 700 mm (Fig. 4). Fishing mortalities that would achieve an SPR of 0.3 or higher ranged from 0.1 to 0.3, and the MLL to obtain an SPR > 0.3 increased with fishing mortality (Fig. 4). Walters and Martell (2004) indicated that sustainable levels of exploitation ( $U_{msy}$ ) are typically about  $0.8 \times M$ , which in this case would be a  $U$  of about 0.1. However, the level of  $U_{msy}$  will vary with the CR for a given fish population, whereas our static SPR management target is invariant to the CR. A  $U$  of 0.1 was predicted to give SPR values exceeding 0.3 for all MLLs considered (Fig. 4). Thus, our study suggested that  $U$  must be held to less than 0.15 under the current MLL of 500 mm to achieve an SPR > 0.3. Similarly, exploitation rates at or exceeding 0.3 would cause SPR values to drop below typical management targets unless the MLL was set at 700 mm or higher.

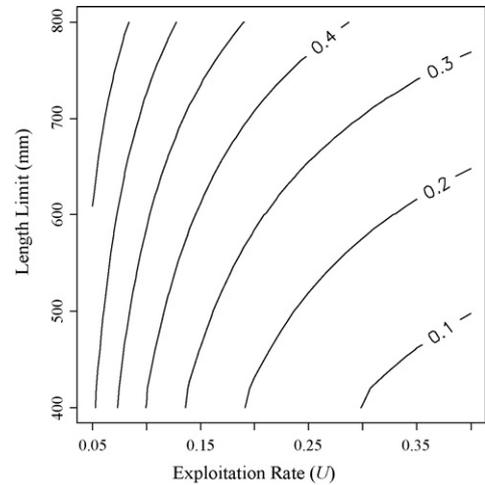


Fig. 4. Isopleths of the spawning potential ratio (SPR) on harvest exploitation rate ( $U$ , x-axis) and minimum length limit (mm, y-axis). Values of SPR below 0.3 are usually indicative of recruitment overfishing.

The yield isopleths showed highest yields at relatively high exploitation rates combined with high MLL's (Fig. 5). The model predicted maximum yield (56.7 kg) occurred at a  $U$  of 0.26 and MLL of 689 mm (Fig. 5). However, yield was predicted to be near the maximum if  $U$  was greater than 0.15 and the MLL exceeded 600 mm. Losses in yield would be required to maintain an SPR greater than 0.35. To illustrate this trade-off, consider that an SPR of 0.45 would be obtained at a  $U$  of 0.1 and MLL of 500 mm (Fig. 4), which would be considered a safe harvest policy. However, under this management scenario, the fishery would attain only 85% of the maximum yield (Fig. 5). Such management trade-offs may be necessary to reduce the risk of recruitment overfishing.

We tuned  $R_0$  in Eq. (1) to 100,000 fish, which produced similar total harvest values to the creel survey data (Table 2). However, the model produced estimates of total catch that were substantially lower than the field estimates from Brown (2008), and thus the equilibrium model predicted fewer undersized fish relative to the creel survey data. Our equilibrium model predictions under constant recruitment,  $U = 0.15$ , and a 500-mm MLL found that four out of ten angler caught fish would be harvestable (i.e.,  $\geq 500$  mm), whereas the creel survey data showed that only one out of ten fish caught actually exceeded 500 mm (Table 2).

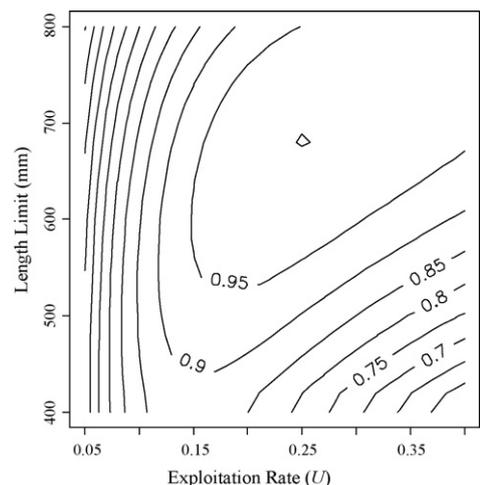


Fig. 5. Yield (kg) isopleths plotted on harvest exploitation rate ( $U$ , x-axis) and minimum length limit (mm, y-axis). Isopleths represent the proportion of MSY.

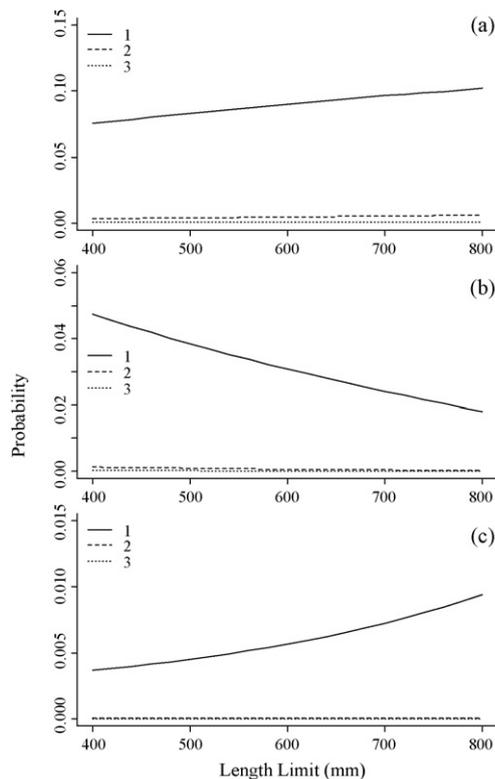
**Table 2**

Comparison of creel survey data from Brown (2008) to model-predicted values of the proportion of angler trips with catch of 0, 1, and 2 fish per trip for fish harvested ( $\geq 500$  mm) and total catch (all Murray cod). The value of  $\lambda$  is the catch/196,299 trips for harvested fish and all fish from Brown (2008) and the model-predicted values.

	Brown (2008)		Model predictions	
	Harvest	Total catch	Harvest	Total catch
Number of fish	7,450	75,825	7,873	17,911
$\lambda$	0.038	0.386	0.040	0.091
Catch/trip				
0	0.96	0.68	0.96	0.91
1	0.04	0.26	0.04	0.08
2	<0.01	0.05	<0.01	<0.01

We explored this discrepancy using a wide range of model parameters including the stochastic recruitment function. We used a wide range of vulnerability parameters and fishing mortality rates to explore conditions where the model would replicate the high catch of small fish relative to fish over 500 mm seen in the creel survey data, but none produced only a 10% occurrence of harvestable fish in angler catches. We explored the log normally distributed stochastic recruitment component to Eq. (1), and found that a ( $\sigma_R$ ) of 0.8 around average annual age-1 abundance could cause catch of harvested fish to represent only 10% of the total catch in years following above average recruitment.

The equilibrium simulations predicted that angler catch, harvest, and catch of trophy fish was influenced by the MLL for Murray cod (Fig. 6). The probability of landing a Murray cod (of any size) increased as the length limit increased (Fig. 6a). For example, our model predicted that an increase in the MLL from 500 to 700 mm would result in a 16% increase in the probability of landing a Mur-



**Fig. 6.** Probability of capturing one (solid line), two (dashed line), or three (dotted line) Murray cod of any size (panel A), legal-sized ( $TL > MLL$ ; panel B), or trophy-sized ( $TL > 1000$  mm; panel C) per-angler trip across a range of minimum length limits at a harvest exploitation rate ( $U$ ) of 0.15.

**Table 3**

Elasticity of spawning potential ratio (SPR) and yield to changes in 10 of the model parameters. Elasticity was calculated as the proportional change in SPR and yield resulting from a 5% increase in the parameter value. For example, yield decreased by 240% with a 5% increase in  $M$ .

Parameter	Elasticity	
	SPR	Yield
$M$	0.68	-2.40
$D$	-0.02	-0.03
$L_{low}$	0.13	0.03
$L_{high}$	-0.55	0.32
$L_{\infty}$	-0.36	4.86
$K$	-0.23	3.31
$CR$		0.06
$A_{mat}$	-0.35	-0.03
$TL_r$	0.61	-2.17
$c$	0.11	-2.81

ray cod. This translated to a predicted increase in the number of successful trips (i.e., trips with at least one fish landed) from 1 out of 12 trips to 1 out of 10. This was due to increased fish abundance resulting from increased recruitment and protection of adult fish by the higher MLL. Thus, if maximizing angler catch were a priority for Murray cod fisheries then a large MLL would be optimal. However, the probability of harvesting a Murray cod declined with increasing MLL (Fig. 6b) due to losses of fish via natural mortality before they grow past the legal length. An increase in the MLL from 500 to 700 mm would decrease the trip harvest success rate by 37% from 1 in 26 trips to 1 in 42. Our model predicted that the probability of landing a trophy-sized Murray cod increased by 60% with an increase in the MLL from 500 to 700 mm (Fig. 6c), which corresponds to an increase in the trip success rate from one out of 222 trips to one out of 138 trips. These analyses demonstrate the trade offs associated with various MLL's, because regulations that provide high numbers of fish harvested (e.g., 400–500 MLL) also result in a higher risk of overfishing (Fig. 4), lower overall angler catch rates, and lower occurrence of trophy fish due to higher exploitation (Fig. 6).

Elasticity analysis showed that the model overall was most sensitive to changes in natural mortality and growth parameters (Table 3). The SPR was most sensitive to natural mortality parameters  $M$  (instantaneous natural mortality) and  $TL_r$  (mortality reference length) followed by  $L_{high}$  (maximum vulnerable length). Equilibrium yield was very sensitive to changes in growth parameters ( $L_{\infty}$  and  $K$ ) and mortality parameters ( $M$ ,  $TL_r$ , and  $c$ ). SPR and yield were robust to perturbations in discard mortality ( $D$ ) and the length at first capture ( $L_{low}$ ).

Plots of SPR and yield across a wide range of parameter values indicated that most parameters had a nearly linear affect over the parameter ranges examined, with the exception of  $M$ ,  $K$  and  $CR$  (Figs. 7 and 8). Linear relationships suggest that elasticity estimates are valid across a wide range of parameter uncertainty. However, non-linear trends for  $M$ ,  $K$  and  $CR$  suggest that the influence of these parameter on yield and SPR depends on the assumed parameter value. For example,  $K$  had a stronger influence (steeper slope) on SPR at low  $K$  values than at high  $K$  values (Fig. 7f). Similarly,  $M$  had a stronger influence on yield at low  $M$  values than high (Fig. 8a). Yield was relatively insensitive to changes in  $CR$  when  $CR$  was greater than 10, but was highly sensitive when  $CR$  was less than 10 (Fig. 8d).

### 3. Discussion

Our results infer that annual exploitation rates should not exceed about 0.3 for Murray cod fisheries unless the MLL was 700 mm or higher. There are no previously published estimates of

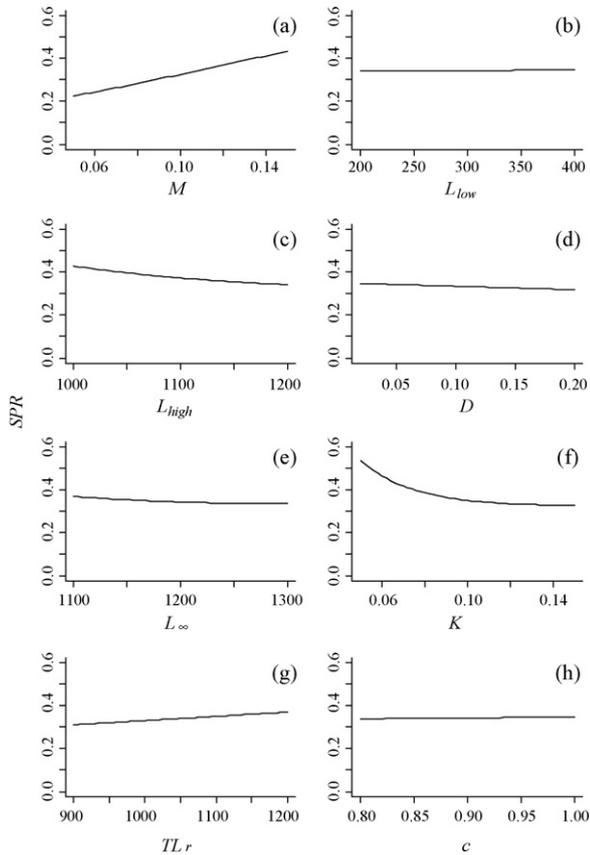


Fig. 7. Sensitivity analyses showing equilibrium SPR as a function of varying eight model parameters.

fishing mortality for Murray cod. However, recent tagging experiments have indicated that annual exploitation could exceed 0.3 for fish in the 600–750 mm size for Murray cod in the Middle Murray River (C. Todd, Arthur Rylah Institute for Environmental Research, personal communication). Values of SPR below 30% are typically considered at risk of recruitment overfishing (Mace, 1994; Clark, 2002), and thus our results suggest that exploitation rates of 0.3 would put Murray cod stocks at risk of recruitment overfishing regardless of the MLL. Future research should include estimates of fishing mortality, preferably using a variable reward system correcting for angler non-reporting (e.g., Pine et al., 2003), telemetry methods (e.g., Hightower et al., 2001), or estimates of fish harvest from creel surveys divided by estimates of fish population size. Such estimates would substantially enhance resource managers' ability to improve Murray cod fisheries, and results of this study could be used to set management plans when fishing mortality is better described.

We used equilibrium analysis that is useful for predicting long-term average responses to changes in MLLs, but may not predict fishery characteristics in the short term if recruitment is highly variable. Our equilibrium model predictions showed substantially less young fish in the population than creel survey data, and the model indicated that variable recruitment could have caused the observed trend. Rowland (2005) noted that Murray cod recruitment in the Murray Darling Basin appeared to increase in the late 1990s and early 2000s. Koster et al. (2004) also found increased electrofishing catches of Murray cod in the Goulburn River in 2003 and 2004 relative to previous sampling efforts in the early 1980s. These indicators suggested that recruitment of Murray cod increased over the last 5–10 years. The coefficient of variation around annual recruit-

ment of 80% has been found for other freshwater predators (Allen and Pine, 2000). The national recreational fishing survey in 2001 found that about 30% of total angler catch was harvested (Henry and Lyle, 2003), which is closer to our equilibrium predictions from the model (40%). Thus, higher than average recruitment in recent years is a probable explanation for the discrepancy between our model and the recent creel survey data.

However, stocking of Murray cod has increased exponentially beginning in the early 1980s, with over one million juvenile Murray cod stocked in VIC and NSW waters by 2002 (Lintermans et al., 2005). The contribution of stocked fish to wild Murray cod populations is not known, and higher recruitment in recent years could result from natural production, stocked fish, or both. Future studies should evaluate the effects of stocked Murray cod on total recruitment to the population and the production of wild fish progeny.

Low angler and electrofishing catches of fish over 500 mm (Koster et al., 2004; Brown, 2008) in the Murray and Goulburn Rivers may indicate that fishing mortality has altered Murray cod size structure and thus SPR. The creel survey data showed that only 4% of angler trips resulted in the harvest of a Murray cod with a 500-mm MLL in place (Brown, 2008). Truncation of the age/size structure from fishing mortality could have caused the low number of harvested fish. However, recent reports of higher recruitment would indicate that recruitment overfishing is not currently occurring. Additionally, if larger Murray cod are not vulnerable to fishing gear and/or sampling gear, then the low occurrence of large fish in creels and sampling gear could reflect fish vulnerability rather than fishing mortality. Our model used a dome-shaped vulnerability schedule to include the hypothesis that fish vulnerability

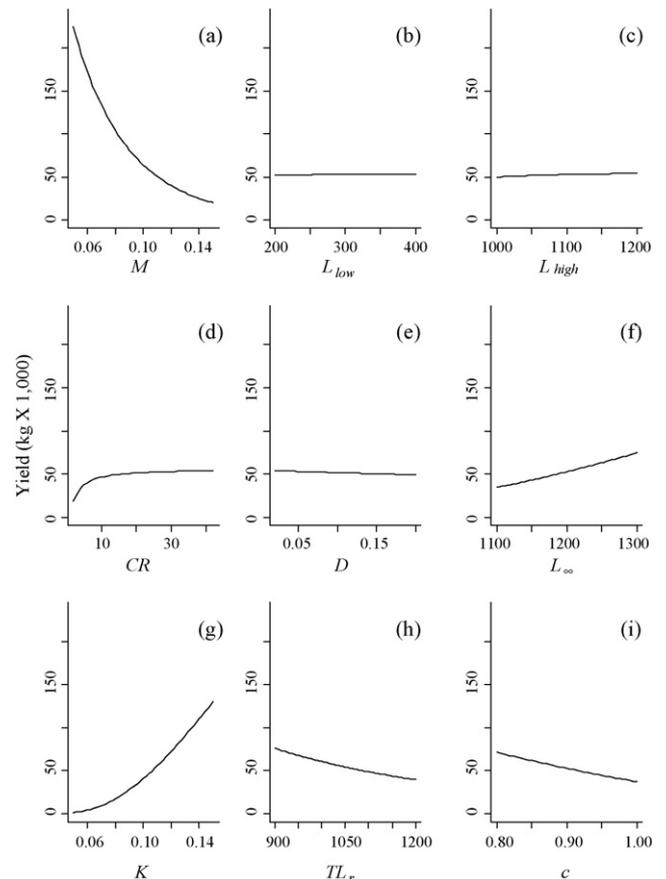


Fig. 8. Sensitivity analyses showing equilibrium yield (kg × 1000) as a function of varying nine model parameters.

declined with size. However, the true vulnerability schedule is not known. The relatively large sensitivity of SPR to the  $L_{high}$  parameters suggests that understanding the shape of the vulnerability curve is important because the vulnerability function becomes more sigmoidal and less dome-shaped as  $L_{high}$  increases. This amplifies the need for size-specific estimates of fishing mortality for Murray cod.

We assumed a 5% discard mortality which was similar to recent work based on common recreational angling practices (VDPI, unpublished data), but measuring discard mortality under a range of fishery conditions will be important in the future. High discard mortality substantially alters the effects of fishing on yield and SPR, with length limits showing little value when discard mortality reaches or exceeds 0.1 for long-lived species like the Murray cod (Coggins et al., 2007). Thus, measures of discard mortality under a range of fishing methods will be important when evaluating potential harvest regulations for Murray cod fisheries. However, our sensitivity analysis showed that SPR and yield were relatively insensitive to variation in discard mortality.

Our model predicted the proportion of angler trips that would be influenced by each hypothesized regulation, which could make regulation choices more interpretable to fisheries managers and anglers. Model outputs common to commercial fisheries stock assessments such as yield or SPR are often vaguely useful in recreational fisheries where anglers evaluate trade offs relative to their personal fishing outcomes. Anglers frequently consider the opportunity to catch large, trophy sized Murray cod an important component of fisheries (Rowland, 2005). Our model output put regulation comparisons on a per-angler trip basis, which may help fishery managers explain regulation trade offs. For example, our analysis showed that increasing the MLL from 500 to 700 mm would increase the proportion of trips where anglers would catch a Murray cod and catch a trophy Murray cod, but decrease the probability they would be able to harvest a fish. Such analyses may help anglers understand the trade offs associated with a range of regulation options. However, variable recruitment can mask effects of regulation changes, and realized changes in angler catches may vary substantially from model predictions if recruitment vulnerability is high (Allen and Pine, 2000). We found evidence of this when comparing the equilibrium model predictions to creel survey data, suggesting that inter-annual variability in recruitment could mask effects of regulation changes.

We assumed that fishing effort would remain similar after each hypothesized regulation change, but shifts in angler effort are an important consideration in open-access recreational fisheries (Cox et al., 2003). Lowering bag limits has caused fishing effort reductions for walleye *Sander vitreus* fisheries in North America (Beard et al., 2003; Fayram and Schmalz, 2006). Alternately, some recreational fisheries remain extremely popular with very stringent size limits in place (Chen et al., 2003). Fishing effort responses to changes in regulations will likely vary with the value anglers place on harvesting fish relative to higher catch rates of fish they must release. Future studies could evaluate model predictions of angler catch by evaluating how fishing effort would change after regulations were enacted (e.g., Beard et al., 2003; Cox et al., 2003; Fayram and Schmalz, 2006), which would be useful for managing open-access recreational fisheries (Cox et al., 2003).

#### 4. Conclusion

The current regulations for Murray cod in Victoria and New South Wales (NSW) includes a seasonal closure during September through November (spawning period), a 500-mm MLL, and only one fish larger than 750 (Victoria) or 1000 (NSW) mm can be taken per-angler daily. The restriction on upper-sized fish is not expected

to influence fishing mortality because of the low occurrence of fish exceeding these sizes both in the field (Brown, 2008) and based on our model predictions. Thus, the MLL and seasonal closure represent the major regulations of fishing mortality. Both NSW and VIC will raise the MLL to 600 mm in 2009, but our model predicts only modest increases in SPR, yield, catch, and catch of trophy-sized fish based on this 100 mm increase in the MLL. Additionally, the model predicted that MLL's of 700–800 mm have the potential to increase yield, total angler catch (number of fish), and the number of trophy fish for Murray cod fisheries, particularly if  $U$  exceeds 0.2. Only total harvest (number of fish) was predicted to decline by increasing the MLL to 700 mm. Thus, our results indicated that higher MLL's should be considered by fisheries managers, pending estimates of the fishing mortality rate for a range of Murray cod stocks.

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