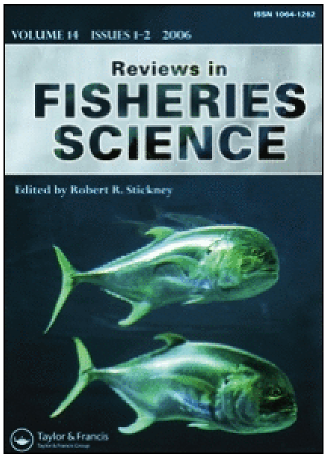

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A Predatory Impact Model and Targeted Stock Enhancement Approach for Optimal Release of Mulloway (*Argyrosomus japonicus*)

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*Habitat, diet, and life history information were used to estimate appropriate stocking density and the potential predatory impact of a stocked finfish. Our Predatory Impact Model uses data from the literature for fish in freshwater or estuarine habitats. Model simulations were run for the Georges River Recreational Fishing Haven (RFH), Sydney, to evaluate appropriate stocking density and associated predatory impact. The estuary contained about 1,760,000 m^2 of key nursery habitat for mulloway (*Argyrosomus japonicus*), and 10% of mysid shrimp production within this habitat was assigned to support stocked fish, as mysids represent the immediate forage requirements of stocked mulloway. Given these values, this section of river could support 17,500 stocked mulloway of 8 cm TL. During the first 3.5 years post stocking, when mulloway are predominantly estuarine residents, predatory impact includes 1 t mysid shrimp, 80 t forage fish, 45 t prawns, 3 t miscellaneous invertebrates and 5 t cephalopods. For comparison, this predatory impact represents 107%, 154%, and 24% of the commercial fishery in Botany Bay/Georges River for forage fish, prawns, and cephalopods, respectively, for 3.5 years before the declaration of the RFH. To maximize the benefit of the approach, a targeted approach to stocking should be taken. Stocked fish should be stocked directly into key habitats, as opposed to being released from a few shore-based sites within the estuarine system.*

Keywords stocking density, key habitat, *Argyrosomus japonicus*, targeted stocking

INTRODUCTION

Advancing marine stocking as a science and an accepted approach to managing fisheries and overcoming recruitment and habitat limitations involves adopting a responsible and scientific approach to the practice (Blankenship and Leber, 1995). Recruitment limitation occurs when there are physical or biological barriers that reduce larval or juvenile recruitment into estuaries, through high mortality or decreased influx of propagules. Recruitment limitation is a characteristic of urbanized estuaries, where nursery areas that support larval or juvenile fish are often destroyed or modified (Gibbs, 2001; Smith and Suthers, 2000), or reduced environmental flows limit recruitment or spawning cues. Urbanized estuaries are often severely impacted by human development; however, high levels of runoff and associated eutrophication may increase the productive capacity of an estuary. Recruitment limitation and enhanced productivity present a justification and opportunity for stocking (Doherty, 1999; Bell, 2004). Introducing juvenile predatory fish into these systems may have a further positive effect by enhancing production at lower trophic levels (e.g., Reznick and Ghalambor, 2005).

Potential adverse effects of stocking include genetically altering wild stocks (Utter, 1998), and overstocking, which can displace wild conspecifics and predators (Leber et al., 1998; Taylor et al., 2005). Quantitative methods are needed to minimize adverse effects of stocking and to estimate appropriate stocking density through the appraisal of the ecological characteristics of target species and ecosystems. Several methods have been proposed to address stocking density (Welcomme, 1998), but these are targeted toward achieving a desired production, rather than an assessment of the resources an ecosystem can support. Stock enhancement programs rarely undertake large-scale assessments of carrying capacity, and the inherent variation in

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estuarine and marine ecosystems precludes the application of these to stocking density estimation. Numerical models already exist to estimate various aspects of marine ecosystems using biometric data (Pauly, 1980; Pauly, 1986; Pauly et al., 2000). In the absence of comprehensive assessments of carrying capacity (e.g., Salvanes et al., 1995; Cooney, 1993), management can minimize overstocking by estimating appropriate stocking density through appraisal of the ecological characteristics of the target ecosystem and species. This involves pilot studies and targeting stocking for appropriate areas while accounting for the ecosystem's capacity to support additional recruits and the predatory impact of those recruits (Taylor et al., 2005). A new approach to refining stocking density is proposed, using published models, biometric information, and other easily obtained measurements.

The approach will allow appropriate stocking density to be estimated at the outset of each stocking event, using instantaneous estimates of key organism abundance in the target ecosystem. Component models use growth and population parameters, including maximum length and weight, the von-Bertelanffy growth coefficient, and habitat specific parameters such as temperature and forage production capacity. The aspect ratio of the caudal fin is also used in the component models to indirectly measure the gross growth efficiency of the fish (Pauly, 1989).

This novel approach to stocking density and predatory impact assessment is applied to mulloway, *Argyrosomus japonicus* (Sciaenidae), in the Georges River, New South Wales. Mulloway are an elusive sportfish endemic to the estuarine and coastal areas of southern Australia, southern Africa, and China. The species is fast growing, reaching the current NSW minimum legal length (MLL) of 47 cm in about 24 months. Mulloway juveniles depend on deep water riverine habitat (Taylor et al., 2006b) and are generally resident within estuaries and near-shore areas until age 4, when larger fish can undertake coastal migrations. The Georges River estuary (S33.998°, E151.155°) extends 50 km inland, where the upper tidal limit is bounded by a weir. The 800-km^2 catchment of the Georges River discharges 3.2×10^8 m^3 of water annually into Botany Bay and has a waterway area of 12 km^2, with 2 km^2 of mangroves and <1 km^2 of seagrass and salt marsh. The estuary receives urban and industrial pollution inputs (Heath et al., 1980) and was declared a Recreational Fishing Haven (RFH) in 2000, with a complete buy back of all commercial fishing licenses by the NSW state government, thus prohibiting all commercial fishing in the estuary.

GENERAL MODEL DESCRIPTION

We use published models, size-specific habitat and diet data, and key life history parameters, to calculate consumption, stocking density, and predatory impact (Figure 1). The model was constrained for the 4-year period of estuarine residency (up to 3.5 years post stocking), when mulloway become sexually mature (Silberschneider and Gray, 2005). Matrix calculations were performed using Matlab (The Mathworks Inc., Natick, Massachusetts, USA).

Component Models

Initially, length-mass and length-age relationships were used to allow switching between size or age and corresponding mass

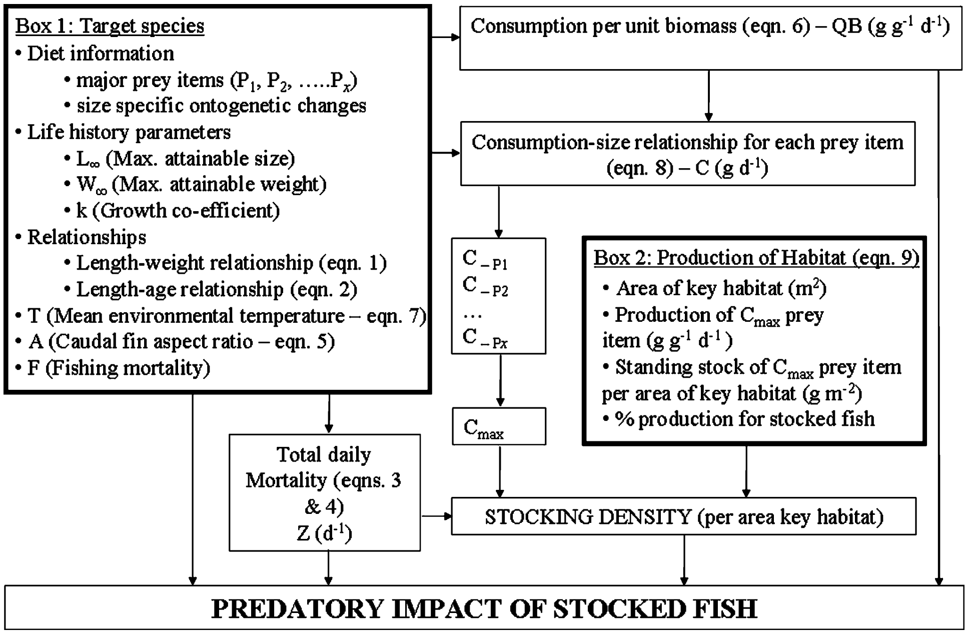

Figure 1 Conceptual Predatory Impact Model. Consumption per unit biomass calculated using parameters in Box 1 is expressed as a consumption-size relationship for each prey item. The first maximum value in this relationship determines C_{max}—the estimated maximum immediate forage requirements of stocked fish. This, in conjunction with production estimates from Box 2, determines stocking density. Input values for the target species (Box 1 and Box 2) are easily obtained from the literature or limited field sampling.

(for consumption estimations) and length values (for dietary classification). The length-mass relationship is of the form:

$$W_t = a \cdot L_t^b \tag{1}$$

where W_t is mass (g) at time t, L_t is total length (TL, cm) at time t in centimeters, and a and b are constants. The length-age relationship follows the form of the von-Bertelanffy growth equation:

$$L_t = L_\infty \cdot (1 - e^{-K(t-t0)}) \tag{2}$$

where L_t is length (cm) at time t, K is the growth rate (y^{-1}), L_∞ is the maximum obtainable total length (cm) and t_0 is the theoretical age (y) at which $L_t = 0$ cm.

Natural mortality (M) was estimated from life history parameters and temperature using the following equation (Pauly, 1980):

$$\log M = -0.2107 - 0.0824 \log W_\infty + 0.6757 \log K + 0.4627 \log T \tag{3}$$

where M is the estimated rate of natural mortality (y^{-1}), W_∞ is the maximum obtainable mass (g), and T is the annual mean environmental temperature (°C). The total instantaneous rate of mortality (Z; y^{-1}) was calculated from fishing mortality (F) and estimated natural mortality (Figure 1; M):

$$Z = F + M \tag{4}$$

For those lengths smaller than the minimum legal length, F is set to 0.

Daily consumption was estimated using life history parameters, temperature, and morphological parameters. The morphological parameters gave an indication of gross growth efficiency, using an index of swimming activity obtained from the aspect ration of the caudal fin, calculated from (Pauly, 1989):

$$A = H^2 \cdot S \tag{5}$$

where H is the maximum height of the caudal fin, and S is the surface area of the caudal fin. A was expressed as a linear relationship with TL.

Daily consumption per unit biomass (QB; g g^{-1} d^{-1}) was calculated using (Palomares and Pauly, 1998):

$$\log_{10}(QB) = 7.964 - 0.204 \cdot \log_{10}(W_\infty) - 1.965 \cdot T' + 0.083 \cdot A + 0.532 \cdot h + 0.398 \cdot d \tag{6}$$

where h and d are logical values; $h = 1$ and $d = 0$ if the species is a herbivore, $h = 0$ and $d = 1$ if the species is a detritivore, and $h = 0$ and $d = 0$ if the species is a carnivore. Temperature was expressed in this model as T':

$$T' = 1000 \cdot (T + 273.15)^{-1} \tag{7}$$

Predatory Impact Model

The parameter inputs above were common for all sizes of mulloway modeled, with the exception of F, which was set to 0 for fish <47 cm and 0.2 for fish >47 cm (Table 1). Diet information (% of each prey type in diet) and A change with size, so they were included in the model as relationships with total length. Using these data and associated component models listed above, the daily predation pressure (C; g d^{-1}) of a single fish on each target prey species was calculated from the length at stocking (8 cm) to 75 cm (age 4):

$$C_x = QB \cdot W_t \cdot p_x \tag{8}$$

where p_x was the proportion of diet of prey species x, and QB and W_t are as described above. C values form the basis of stocking density calculations, and the magnitude of the values changed for major prey species as fish grew and switched between prey species. C values also varied across size depending on the mass of the stocked fish and the proportion of the prey species in the

Table 1 Parameter values for Predatory Impact Model run

Parameter	Name	Value	Source
L_∞	Asymptotic length	132 cm	Silberschneider & Gray (2005)
W_∞	Asymptotic mass	44,000 g	Estimated
a		$1.08e^{-5\#}$	Silberschneider & Gray (2005)
b		$4.73^{\#}$	Silberschneider & Gray (2005)
K	Growth coefficient	0.197 y^{-1}	Silberschneider & Gray (2005)
t_0	Time when $L_t = 0$	−0.552	Silberschneider & Gray (2005)
T	Mean annual temperature	17.4°C	Measured
F	Fishing mortality	0.2 y^{-1}	Estimated from unpublished tagging data
H	Height of caudal fin	Range 14–148 mm	Measured
S	Surface area of caudal fin	Range 190–13,781 mm	Measured
Pd	Production of C$_{\max}$ forage species	0.022 g g d^{-1}	Wooldridge (1986)*
SS	Standing stock of C$_{\max}$ forage species	1.21 g m^{-2}	Measured
Ah	Area of key habitat	1,760,737 m^2	Measured
Sf	Production assigned to stocked fish	0.1	Estimated from field data

#These parameters were excluded from the sensitivity analysis.

*Daily production estimates for the temperate estuarine mysid *Rhopalophthalmus terranatalis*.

diet. Peaks in C values represented the maximum daily predation pressure an individual stocked fish would have on a prey species. The first maxima in C encountered as the fish grows (C_{max}) was the immediate maximum predation pressure exerted by an individual stocked fish on a prey species, and was passed through the model as the factor limiting stocking density (Figure 1). In order to keep the model practical, C values that occurred after C_{max} were not considered in calculations of stocking density, thus assuming that consumption of prey species whose maxima in C occurs after C_{max} were supported. Stocking density was calculated based on the production available in the key habitat to support this C_{max} value, using instantaneous estimates of production (*Pd*) and standing stock (*SS*) of the C_{max} species at the time of stocking, rather than relying on models to predict production of other prey species in subsequent years. Thus, the model only considered the immediate forage needs of stocked fish when estimating stocking density, and assumed that if these needs are not met the other C values will not be reached and are not important.

The C_{max} value was evaluated in terms of production to estimate stocking density (Figure 1). The approach required knowledge of the habitat requirements of the target species. If a stocked species has specific habitat requirements, or is dependant on refugia and local foraging arenas (Walters and Martell, 2004), then only production in these arenas would be exploited by stocked fish. If fish are forced to venture away from refugia to forage, predation risk and search time are increased, and associated mortality may lead to low survival of stocked fish. Production (P) of the C_{max} species in the target system was determined by (Figure 1):

$$P = Pd \cdot SS \cdot Ah \cdot Sf \tag{9}$$

where P is the productive capacity of the C_{max} species for each unit of habitat (g m^{-2} d^{-1}), *Pd* is the production per unit biomass of the C_{max} species (g g^{-1} d^{-1}), *SS* is the standing stock of the C_{max} species in the key habitat (g m^{-2}), *Ah* is the area of key habitat in the ecosystem to be stocked (m^2), as determined through habitat surveys, and *Sf* is the proportion of C_{max} species production assigned to stocked fish. While *Sf* may be arbitrarily assigned, estimates may be obtained from surveys of competitors for the relevant prey species. For mulloway, *Pd* was obtained from the literature, and *SS* values were determined from trawl surveys conducted within the key habitat in the Georges River. The matrix of production estimates for each habitat patch was divided by the C_{max} value to estimate the number of fish of the corresponding size the habitat patch could support. Mortality estimates were then applied to back calculate density of fish at the target stocking size (e.g., 8 cm) each habitat patch could support (Figure 1).

The above consumption, stocking density, and mortality estimates were applied to give an appraisal of the predatory impact of stocked fish in the ecosystem (Figure 1). Predatory impact was evaluated for each prey species and allowed an assessment of the potential impacts of stocking on the ecosystem and the catches of commercially important species. These estimates also allowed the stocking effort to be evaluated in terms of production removed from the system for those organisms other than C_{max} prey species. If a major prey item was a commercial species, total predatory impact of stocked fish (P_{max}) was evaluated as the proportion of commercial catch for that species in the target area for the time from stocking to departure from the estuary.

Sensitivity Analysis

A sensitivity analysis was undertaken to assess the sensitivity of the model to changes in parameter estimates from the Predatory Impact Model. Parameters W_∞, L_∞, K, T, *Pd*, *SS*, *Sf*, and aspect ratio estimates were varied from default values (Table 1) by ±10% of the default value, giving 3 values for each parameter. Parameters used in the length-mass relationship were not varied for the sensitivity analysis, as they do not affect stocking density or predatory impact estimates. Combinations of parameter values were randomly selected for 10,000 model simulations to demonstrate the effect of cumulative parameter variation on estimates of stocking density and total predatory impact.

RESULTS

Mulloway Stocking Density and Predatory Impact

The model was run to determine the appropriate stocking density and predatory impact for mulloway in the Georges River, Sydney (Figure 2). Parameter values for this model run are given in Table 1, and the habitat map is shown in Figure 2. Mean modeled *QB* values were 0.69 ± 0.01% body mass d^{-1} (mean ± SE). The highest *QB* value of 0.75% body mass d^{-1} occurred at the maximum size modeled, 75 cm TL. These values are comparable to experimental measurements of 0.73 ± 0.08% body mass d^{-1}, taken from mulloway stomach contents (Taylor et al., 2006a). Modeled C values (Figure 3) show that maxima in C are only reached for mysids and prawns, while stocked mulloway are estuarine residents. The first maxima in C as the fish grows is for mysids, giving a C_{max} value of 0.29 g d^{-1} (Figure 3; Table 2), at 28 cm TL. Although maximum C values ranged from 0.29–24.75 g d^{-1} (Table 2), C values for forage fish (including the species *Pseudogobius olorum*, *Hyperlophus vitattus, Acanthopagrus australis, Mugil cephalus,* and *Ambassis jacksoniensis*; Taylor et al., 2006a) and cephalopods do not peak or plateau during the period of estuarine residency (Figure 3), as their importance does not decrease over this time. Also, the peak in consumption for prawns (Figure 3; Table 2) does not occur until stocked mulloway reach a length of ~60 cm or 2.6 years after stocking. During this time stocked fish have generally moved out of their stocked habitat, are foraging outside deep-water habitat, and some may have even migrated to different estuaries. Given the production estimates (Table 1) and a C_{max} value of 0.29 g mysid shrimp d^{-1}, the Georges River

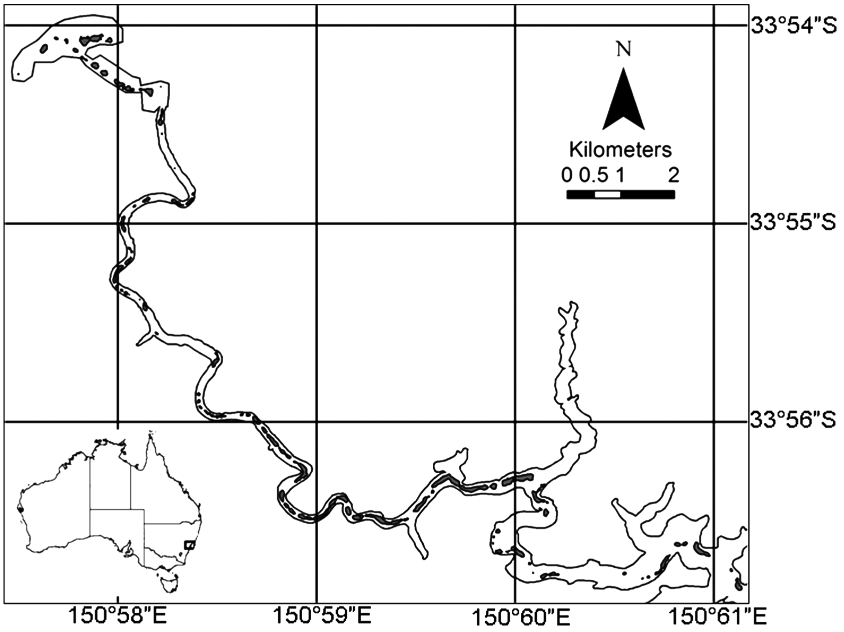

Figure 2 Map of the Georges River, New South Wales. Habitat patches of deep holes (>5 m) are shaded.

could support around 16,100 mulloway of 28 cm TL, which equates to 17,500 mulloway of 8 cm TL, given mortality estimates obtained using Equations 3 and 4. Stocking density was estimated for each key habitat patch to allow targeted releases at modeled densities directly into habitat patches (Figure 2).

While estimates of predatory impact closely reflected diet data, magnitude was dependent on the mass of the fish. The total predatory impact increased over the period of estuarine residency (Figure 4a). Estimated total predatory impact over 3.5 years post stocking (Table 2) was compared with former commercial catch rates in the Georges River estuary over the same time period, for those species that were commercially exploited (Table 2). With the exception of prawns, the estimated predatory impact was comparable to or less than the former commercial catch (Table 2), indicating reasonable associated impacts of stocking at the estimated density.

Sensitivity Analysis

Model simulations using random 10% variations in parameter values produced significant variations in stocking density

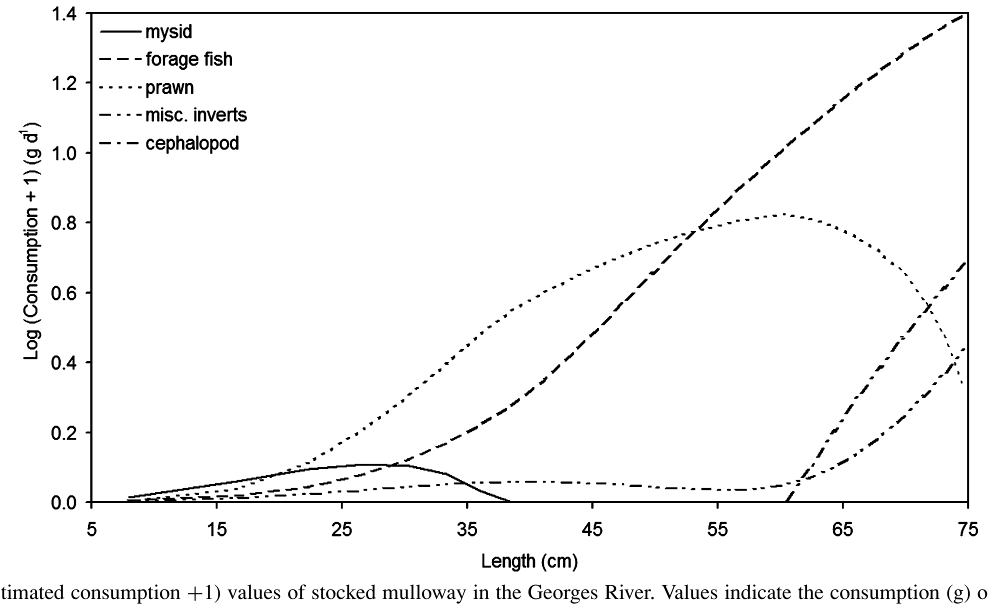

Figure 3 Log$_{10}$ (estimated consumption +1) values of stocked mulloway in the Georges River. Values indicate the consumption (g) of an individual stocked mulloway per day. The first maxima encountered after stocking is for mysids, giving a C$_{max}$ value of 0.29 g d^{-1} at 28 cm TL.

Table 2 Consumption and predatory impact estimates for stocked fish

Prey Item	Peaks in C Values (g d^{-1})[*]	Total Predatory Impact (t)[#]	Commercial Catch (t)[#]	% Commercial Catch
Mysid shrimp	0.29[^]	1	—	—
Forage fish	24.75	80	74	107%
Prawns	5.77	45	29	154%
Misc. inverts	1.85	3	—	—
Cephalopods	3.98	5	21	24%

[#] These values are totals for the entire post-stocking period of estuarine residency (~3.5 y). Commercial catch is the total reported commercial catch in the Botany Bay/Georges River Recreational Fishing Haven for 3.5 years before the establishment of the recreational fishing haven 1997–2001 (NSW DPI Commercial Catch Statistics Database).

[^] This value is the C_{max} value, corresponding to the first peak in consumption in Figure 3.

[*] Note these are maximum values for the period of estuarine residency only, as peaks in C may not be attained during the period of mulloway estuarine residency for these species and may occur after fish leave the estuary.

and predatory impact estimates (Figure 5a, b). Stocking density estimates were sensitive to variations in all parameters, producing varied estimates between unadjusted parameter values and parameter values adjusted by ±10%. Predatory impact estimates varied similarly, but were largely insensitive to variations in W_∞. Sensitivity analyses showed that increasing aspect ratio had an inverse effect on predatory impact relative to stocking density (Figure 5). Increasing the parameters affecting growth (W_∞, L_∞, K, T) generally led to lower predatory impact estimates, while increasing the parameters related to production (*Pd*, *SS*, *Sf*) increased both stocking density and predatory impact estimates. The smallest estimates for stocking density and predatory impact were produced using parameter combinations containing reduced production estimates and conversely for elevated production estimates. Variation of *Pd*, *SS,* and *Sf* produced the largest changes in stocking density (Figure 5a) and predatory impact estimates (Figure 5b). While this indicates that estimates were most sensitive to instantaneous rates of production, stocking density and predatory impact estimates obtained using varied parameter values were generally within ±10% of estimates using default values (17,500 8-cm fish and 135 t, respectively).

DISCUSSION

This approach provides the first model to assess predatory impact of stocked finfish. The Predatory Impact Model is a method for estimating stocking density and predatory impact using readily available data, with model estimates affected only slightly (±10%) by changes in parameter values. Higher aspect ratio values lower stocking density estimates as fish consume more and expend more energy in swimming, and this is evident in the greater predatory impact estimates for higher aspect ratio values. While estimates of W_∞, L_∞, and K are documented for many fish species, and aspect ratio and *SS* (standing stock of forage species) can be easily measured, the parameters *Pd* (production of forage species) and *Sf* (proportion of forage species production assigned to stocked fish) are harder to estimate. These values have the greatest effect on stocking density and associated predatory impact. Values of *Sf* may be conservative and arbitrary, with $Sf = 0.05$ potentially representing a trivial harvest, and $Sf = 0.15$ probably resulting in density estimates that are too high and lead to displacement of competitors and conspecifics. It is important to census the release site to evaluate competitor/conspecific abundance in the release habitat and provide a semi-quantitative basis for estimation of *Sf.* Diet information also has a marked effect on predatory impact estimates, as proportions of forage items in the diet directly determines the proportion of total predatory impact assigned to a specific forage type/species. The trends of consumption and predatory impact with length (Figure 3) will largely mirror that of the diet data; however, the magnitude of the estimates are adjusted by mortality rates and increases in mass.

Two key assumptions of the model are that C_{max} is the factor limiting the density of stocked fish, and the standing stock of the C_{max} prey species is constant from the time of measurement until stocked fish grow to the size that C_{max} is reached. As C_{max} relates to only one prey species, it is assumed that prey resources required by stocked fish as they grow larger are present in the ecosystem. This approach was taken to estimating stocking density, as stocked fish will move out of the key habitat as they grow, possibly having a more uniform distribution within the ecosystem as predation risk lessens. As this occurs, habitat requirements may become less specific, predatory impact will be spread over a larger area within the estuary, and fish may also start targeting prey resources in areas adjacent to the estuary. Therefore, consumption and predation pressure exerted later in life will be difficult to relate to production for the estimation of stocking density. Production values for these prey species must be forecasted rather than measured instantaneously, and the location of stocked fish in subsequent years may be difficult to determine, introducing greater uncertainty to estimates.

Former commercial catch in recreational fishing havens can give an indication of the abundance of potential available resources in the system. Predators may still be in an altered equilibrium, with decreased forage abundance after decades of exploitation; however, an abrupt cessation in harvest will free up these resources to support enhanced growth or additional recruits in the system. When estimates are available, this can be related to potential predatory impact of stocked fish by the Predatory Impact Model. Although commercial catch is a useful standard against which to measure predatory impact (Table 2), these are by no means an unbiased estimate of organism abundance in the system. The prey of stocked fish, particularly smaller forage fish and those organisms at lower trophic levels, may not be commonly targeted by commercial fishing or may represent a bycatch of fishing. With the advent of Recreational Fishing Havens, former commercial catches provide an indicator of potential available carrying capacity in the ecosystem, particularly for recruitment limited species.

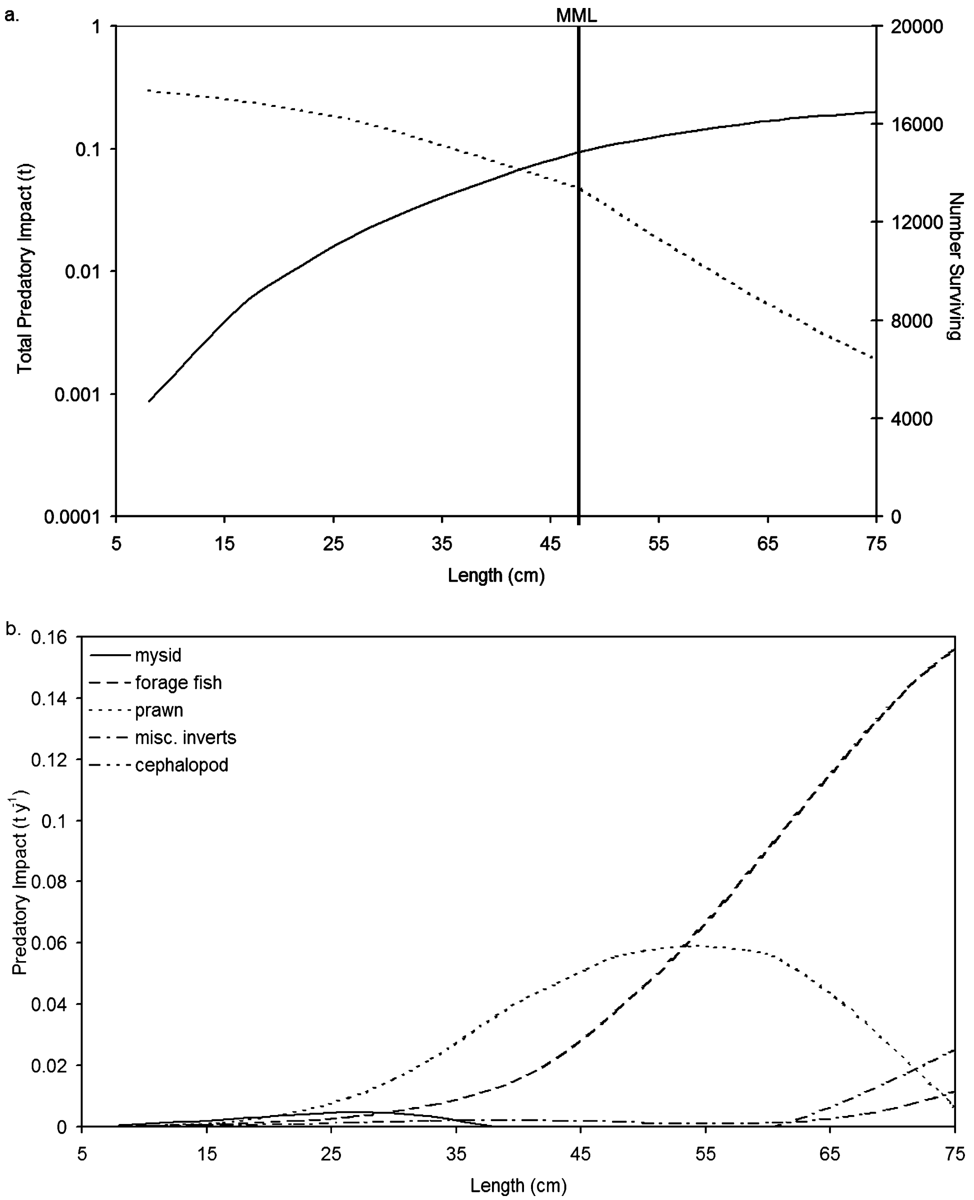

Figure 4 Estimates of total predatory impact (solid line) and number of fish surviving (dotted line) for a cohort of 17,500 mulloway of 8 cm TL (a), and yearly rate of predatory impact (b) for stocked mulloway in Georges River during the period of estuarine residency. Minimum legal length (MML) of 47 cm TL is indicated in (a). This corresponded with a greater total mortality (Z) rate.

Natural mortality estimates obtained using Equation 3 were similar to those measured for wild mulloway in South Australia (Hall, 1986) and New South Wales (Silberschneider and Gray, 2005). While natural mortality is difficult to measure (Pauly, 1980), validation of model estimates for stocked fish should be attempted, as incorrect mortality values will affect both stocking density and predatory impact estimates. Stocking strategies affect mortality of stocked fish (Leber et al., 1997), including naivety of stocked fish toward both predators and prey (Olla et al., 1998, Suboski and Templeton, 1989), and should be considered alongside validation of natural mortality estimates. Transport mortality and naivety-associated mortality can be included in estimates of Z for a period after release. Fishing mortality estimates in our simulations were set to 0.2 y^{-1}, based on recreational mulloway fishery tag recapture data in the Georges River (Taylor; unpublished data). Natural and total mortality estimates may be calculated through alternative methods (Ehrhardt and Ault, 1992; Hoenig, 1983); however, a more robust approach provides an integrated estimate of mortality derived from the likelihood functions of several different methods of estimation (Hall et al., 2004). Further development of the model for mulloway and other species or estuaries should evaluate the feasibility of this approach. Given these considerations, the Predatory Impact Model may underestimate mortality for early life stages

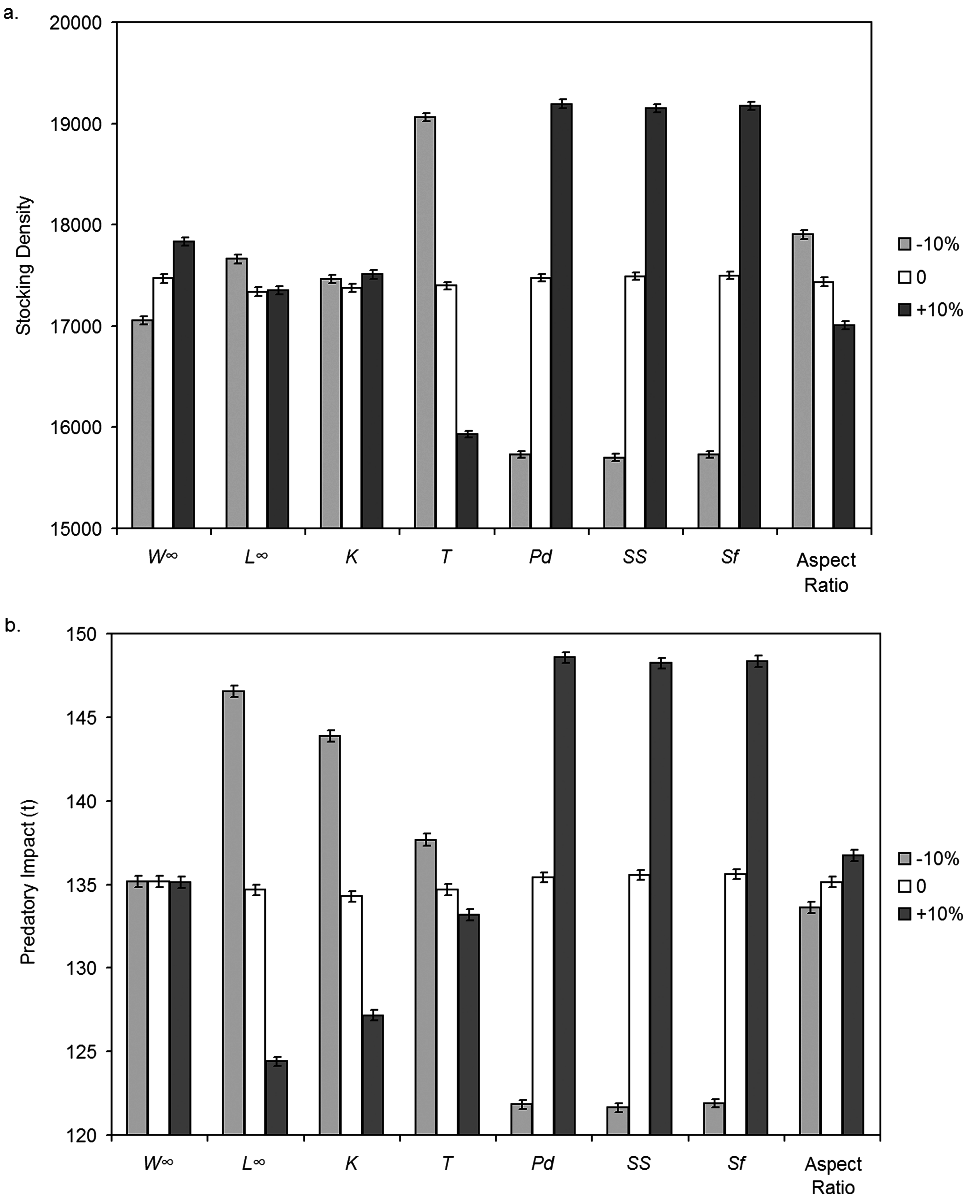

Figure 5 Sensitivity analysis for the Predatory Impact Model. Mean ± SE stocking density (a) and predatory impact, and (b) estimates for 10,000 model simulations with random combinations of unvaried or ±10% varied model parameters.

of stocked mulloway, and once more accurate mortality values are determined, stocking density at the target size should moderately increase.

Our Predatory Impact Model is intended as a first step in developing both pilot studies and stocking programs in the context of individual ecosystem characteristics. The variability of marine and estuarine systems, particularly when manipulations such as stocking are taking place, necessitates the use of instantaneous estimates rather than long-term trends or ecosystem wide models, although these are useful in interpreting predicted values. Manipulation of ecosystems may even cause unforeseen changes in ecosystem function, such as increased production at lower trophic levels when predation pressure is increased (Christensen and Pauly, 1998; Reznick and Ghalambor, 2005). Christiansen and Pauly (1998) found that given ecosystem development theory (Odum, 1969) and retention and recycling of detrital material, top-predator biomasses may be increased by an order of magnitude within given primary productions. Stocking projects should be aware that these changes could take place and look to detect them in their monitoring programs. These recent findings imply that stocking may enhance the productivity of system, as production at the lower trophic levels may have the capacity to compensate for increases in predator biomass in many systems. While our model has been used for mulloway in the Georges River, there is potential for wider application, as the model is designed to be non-species and non-habitat specific. The component models are equally applicable across different species and freshwater and estuarine habitats and species

(Palomares and Pauly, 1998; Pauly, 1980); however, the model may have to be reworked to account for individual species or ecosystem characteristics.

Targeted Stocking Approach

Habitat is of major importance in the above model, as fish may have specific habitat requirements that relate to predation risk (Walters, 2000; Walters and Martell, 2004), available food sources (Taylor et al., 2006a), and reproduction (Peters et al., 1998). Stocking traditionally involves releasing fish from a convenient location (Yamashita et al., 1994; Leber et al., 1998; Willis et al., 1995) such as a boat ramp or jetty, rather than distributing the stocked fish directly into their key habitats. Stocked fish may have difficulty locating their desired habitat in the face of naivety, predators, tides, currents, and food shortages, which are all circumstances they do not encounter in the hatchery. This approach to releasing fish may not only result in local extinction of prey resources, as stocked fish may remain in the release area for some time (Leber et al., 1998), but also allows for high predation on stocked fish by birds (Johansen et al., 1999) and other predators (Kellison et al., 2002), and the potential for increased exploitation.

To minimize post-stocking predation, starvation, and associated mortality, stocking should be undertaken using a targeted approach. Targeted stocking involves transporting fingerlings directly into key habitats and stocking at the appropriate density for the habitat patch. Targeted stocking requires additional effort to distribute fish, but may result in greater survival, lower environment impact, and minimal displacement of wild conspecifics and predators. While some projects have made an effort to disperse released fish (Støttrup et al., 2002), random distribution would best be replaced by targeted releases at a suitable density. Targeted stocking may even prompt a return to restocking the oceans (e.g., Chan et al., 2003), by releasing eggs into key oceanographic areas such as remotely sensed fronts or eddies.

The effectiveness of the targeted stocking approach and Predatory Impact Model has not been tested with in-field measurements of stocking success and survival. However, it will provide a useful first step when planning enhancement studies. Future work should validate mortality estimates and measure increases in recapture rates and contribution to the fishery when using the approach. The approach will lower the chance of "pilot" or large-scale releases of hatchery-reared fish swamping wild recruitment, as was observed in past projects (Leber et al., 1998).

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