Using a double codend to reduce discard mortality

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Traditional technical strategies for mitigating collateral fishing mortality have involved improving gear selectivity (to reduce bycatch) and, more recently, concomitant changes to onboard handling procedures to reduce some of the negative impacts to the remaining discards. A less common approach is to modify gears physically to minimize deleterious catching mechanisms and subsequent mortalities during fishing. This study aimed to investigate the utility of the latter category of modifications for penaeid trawls by separating a codend into two compartments (termed a double codend) to alleviate interactions between catches. Compared with a conventional design, the double codend significantly reduced the immediate (from 17.1 to 13.8%) and short-term (22.5 to 17.1%) mortalities of discarded juvenile school prawns (*Metapenaeus macleayi*). The effectiveness of the double codend remained independent of other factors known to affect the fate of discarded juvenile *M. macleayi*, including cloud cover and, owing to minimal variability, the weight of the total catch. However, irrespective of the codend configuration, overall mortalities were also positively correlated with the quantity of jellyfish. We conclude that when combined with modifications to improve selectivity and appropriate onboard handling strategies, compartmentalizing codend catches could cumulatively reduce unaccounted fishing mortality.

Keywords: bycatch, discard mortality, *Metapenaeus macleayi*, trawling, unaccounted fishing mortality.

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Introduction

Most technical approaches to mitigating unaccounted fishing mortality from net-based gears have focused on improving the selectivity through changes to the mesh size and/or shape and, where appropriate, the use of bycatch reduction devices (BRDs; for reviews, see Hamley, 1975; Broadhurst, 2000). Based on the premise that the survival of escapees is much greater than that of the organisms brought to the surface and discarded, such refinements are assumed to reduce collateral fatalities (Broadhurst *et al.*, 2006). However, although many modifications to gears have reduced bycatch considerably, none are completely effective, so some unwanted organisms are still caught. A concomitant strategy to address this remaining issue is to develop ancillary technical solutions that minimize associated negative impacts and mortalities to subsequent discards (e.g. Trumble *et al.*, 1995; Gamito and Cabral, 2003; Broadhurst *et al.*, in press).

The fate of discards depends on species-specific tolerances to the cumulative effects of several dominant technical, environmental, and biological factors associated with the particular catching mechanisms (Davis, 2002; Broadhurst *et al.*, 2006). For towed gears, many of the initial and short-term mortalities can be attributed to coarse mechanical interactions among organisms and with netting panels, especially in the codend, where abrasive and/or compressive injuries can be exacerbated by the composition of catches and, more commonly, their increasing volume (e.g. Berghahn *et al.*, 1992; Broadhurst *et al.*, in press).

Because catch volume is a positive function of deployment duration, a simple strategy to mitigate negative impacts is to deploy gears for shorter periods, which has the added benefit of reducing the time that organisms spend in the codend (Berghahn *et al.*, 1992; Parker *et al.*, 2003). A less obvious approach that has been suggested, but not examined in any detail, might be to compartmentalize catches into smaller independent multiple codends and hence to reduce their relative volumes and perhaps the extent of interactions (Broadhurst *et al.*, 2006).

We sought to investigate the potential of such a modification for reducing discard mortality in the Clarence River penaeid trawl fishery in southeastern Australia. All trawlers (114) working in this fishery are required to use BRDs (including the Nordmøre-grid) and square-mesh codends [27-mm mesh hung on the bar (B), and typically 150 B in circumference] to minimize their catches of unwanted teleosts and non-commercial sizes (<15 mm carapace length, CL) of school prawns, *Metapenaeus macleayi*, respectively. Despite these modifications, some organisms and especially small *M. macleayi* are caught and discarded with short-term (5 d) mortalities typically between 15 and 40% (Macbeth *et al.*, 2006; Broadhurst and Uhlmann, 2007; Broadhurst *et al.*, in press). The aim of this study was to determine whether, based on the logic above, such mortalities could be mitigated by compartmentalizing the codend into two independent bags (similar to a so-called trouser trawl—Walsh *et al.*, 1992).

Material and methods

Equipment used

The study was carried out in October 2007 in Lake Wooloweyah (part of the Clarence River system; 29°26′S 153°22′E), New

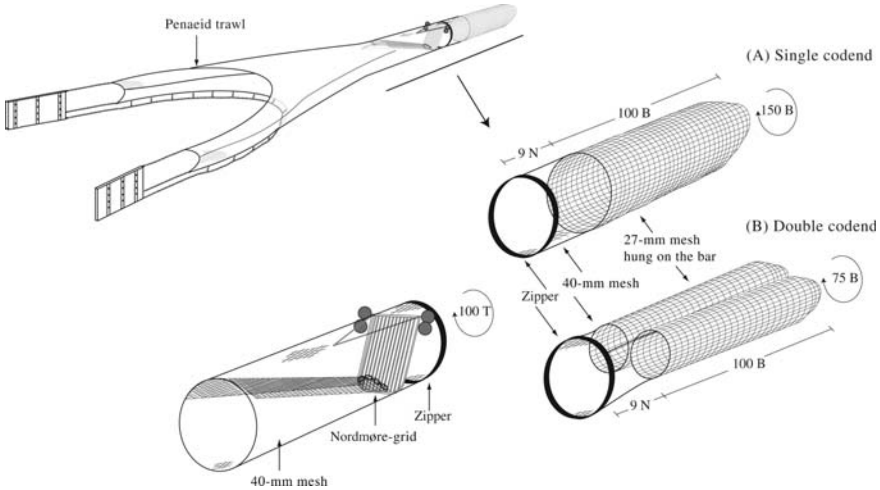

Figure 1. Schematic diagram of the penaeid trawl with the Nordmøre-grid attached to either the (A) single or (B) double codends.

South Wales (NSW). In all, 20 × 2.5-m steel stanchions were secured 3 m apart (in <2 m of water) to the bottom of a small tributary leading into the lake (termed the monitoring site). A 70-m length of rope (diameter, $\o = 10$ mm) was tied to the stanchions to secure up to 64 portable cylindrical cages (0.3 m ø × 0.4 m deep) designed to house discarded *M. macleayi* and made from polyvinyl chloride (PVC) buckets with lids and clips. Each cage had lateral windows covered by 6-mm PVC mesh and was filled with locally collected sediment to a depth of 6 cm. The cages fitted into aerated, square, water-filled PVC containers (75 l) on a dory, enabling them to be transported between the fishing (see below) and monitoring sites.

All fishing was done in the lake using a commercial penaeid trawler (10 m) rigged with identical twin Florida Flyer trawls (each with a headline of 7.3 m; Figure 1). Both trawls had identical Nordmøre-grids (bar spaces of 20 mm), located in an extension section made from 40-mm polyethylene (PE) mesh with a circumference of 100 T (Figure 1). Zippers (Buraschi 146R, 1.45 m long) were secured posterior to the Nordmøre-grids to allow the codends to be changed (Figure 1).

Two codends were used; both consisted of a zippered (1.45 m) anterior section made from 40-mm PE mesh (100 T × 9 N) attached to a posterior section of 27-mm polyamide knotless mesh (twine of ø 2.25 mm) hung on the bar and with a length of 100 B (Figure 1). The first design (termed the single codend) represented a conventional codend and had a posterior circumference of 150 B throughout (Figure 1a). The second design (termed the double codend) consisted of a posterior section with two independent, separate codends or compartments, each measuring 75 B in circumference and similar in design to a pair of trousers (Figure 1b). Once *M. macleayi* entered either compartment or leg of the trousers, they remained independent of *M. macleayi* in the other compartment.

Experimental design and analysis

Between 07:00 and 13:30 on each of 3 d of fishing, the treatment codends were continually alternated between trawls (using the zippers), then used in four independent 60-min deployments in depths of 1–2 m (providing a total of 12 replicate paired deployments). After each deployment, the single and double codends were emptied separately into a partitioned tray (catches in the double codend were evenly distributed between the two compartments and were combined) and their catches simultaneously but separately processed (to ensure identical air exposure and handling times). All non-penaeid bycatch was removed before the *M. macleayi* were separated into retained and unwanted categories using riddlers (see Macbeth *et al.*, 2006, for details). Totals of 80 unwanted *M. macleayi* from each treatment codend were then randomly selected and discarded in groups of ten into eight water-filled cages (i.e. a total of 160 *M. macleayi* in 16 cages from each deployment). Four of the cages containing *M. macleayi* from each treatment codend were sampled immediately (T_0, see below), and the rest were transferred in the dory to the monitoring site and clipped to the line (within 10 min) and sampled at 24 h (T_{24}, see below).

The data collected during each deployment included: the trawl speed ($\mathrm{m\ s^{-1}}$) and depth (m); cloud cover (%); air and tray surface temperature (°C); air exposure of the catch (min); and the numbers and weights (kg) of retained and discarded catches. A Horiba U10 water-quality meter was used to record replicate measures of water temperature (°C), dissolved oxygen ($\mathrm{mg\ l^{-1}}$), pH, and salinity at the surface and bottom of the lake during fishing and at the monitoring site when the cages were attached to the line. At both sample times, the relevant four cages from each of the treatment codends were emptied onto a tray (*M. macleayi* were buried in the sediment). The numbers of live and dead *M. macleayi* were recorded and, if possible, measured to the nearest 1 mm CL.

The catch and survival data were analysed using separate generalized linear mixed models (GLMMs), all of which included the random effects of days, deployments, and for the survival data, cages. The null hypothesis of no differences in the weights of total catches, retained and discarded *M. macleayi* (and CL of the latter), and discarded teleosts and jellyfish, *Catostylus* sp., was investigated between the two treatment codends [all data except CL were $\ln(x + 1)$ transformed]. The independence of the mortality of *M. macleayi* on key covariates (i.e. fixed effects), including codend configuration and sample time, was assessed via binomial GLMMs fitted with a logit link function. The most parsimonious binomial model was chosen based on the lowest Akaike's Information Criterion. All fits were obtained using the lme4 package of the freely available R language.

Table 1. Summary of mean (± s.d.) key environmental, technical, and biological variables collected during the paired deployments of the single and double codends for *M. macleayi*.

Variable	Value	
Technical	Both codends	
Deployment		
Speed (m s^{-1})	1.1 ± 0.1 (12)	
Depth (m)	1.5 ± 0.0 (12)	
Environmental		
Lake		
Temperature (°C)		
Surface	23.2 ± 0.7 (12)	
Bottom	22.8 ± 1.3 (12)	
pH		
Surface	8.8 ± 0.2 (12)	
Bottom	8.8 ± 0.2 (12)	
Dissolved oxygen (mg l^{-1})		
Surface	6.3 ± 0.7 (12)	
Bottom	6.2 ± 0.6 (12)	
Salinity (psu)		
Surface	20.4 ± 1.7 (12)	
Bottom	20.4 ± 2.8 (12)	
Monitoring site		
Temperature (°C)	24.3 ± 0.7 (3)	
pH	8.9 ± 0.0 (3)	
Dissolved oxygen (mg l^{-1})	6.0 ± 0.1 (3)	
Salinity (psu)	20.5 ± 0.9 (3)	
Cloud cover (%)	36.7 ± 34.7 (12)	
Air temperature (°C)	23.5 ± 3.0 (12)	
Tray surface temperature (°C)	26.0 ± 3.7 (12)	
Catch air exposure (min)	15.1 ± 3.8 (12)	
Biological	Single codend	Double codend
Weight of catch (kg)		
Total	12.2 ± 4.5 (12)	11.8 ± 3.9 (12)
Retained *M. macleayi*	9.5 ± 4.1 (12)	9.3 ± 3.4 (12)
Discarded *M. macleayi*	0.8 ± 0.5 (12)	0.7 ± 0.3 (12)
Discarded teleosts	1.0 ± 1.1 (12)	0.9 ± 1.0 (12)
Discarded jellyfish	0.8 ± 1.3 (12)	0.9 ± 1.2 (12)
CL (mm) of trawled-and-monitored *M. macleayi*	13.6 ± 2.6 (903)	13.7 ± 2.0 (916)

Number of replicates in parenthesis; CL, carapace length.

Results

The total catch from the 12 deployments was 288 kg and 23 species, although *M. macleayi* was the most abundant, accounting for almost 245 kg, of which 17.5 kg were discarded (Table 1). Non-penaeid bycatch was dominated by jellyfish (7.4% of the total catch) and small teleosts (8.1%), including silver biddy (*Gerres subfasciatus*), Ramsey's perchlet (*Ambassis marianus*), and southern herring (*Herklotsichthys castelnaui*). All catches remained similar between the codend configurations (Table 1), with GLMMs returning a non-significant effect of this factor for the weights of total catch ($p = 0.82$), retained ($p = 0.96$), and discarded ($p = 0.39$) *M. macleayi*, and the sizes ($p = 0.78$) of the latter, and discarded total teleosts ($p = 0.25$) and jellyfish ($p = 0.26$).

Although a stocking density of 10 discarded *M. macleayi* per cage was attempted, 11 or 12 individuals were placed in eight of the cages. Further, owing to a faulty lid, all ten *M. macleayi* escaped from one of the cages derived from the single codend at T_{24}. These differences resulted in totals of 956 and 964 caged individuals from the single and double codends, respectively (Table 2).

Table 2. Numbers of *M. macleayi* and their percentage mortality for each treatment codend immediately (T_0) and 24 h (T_{24}) after being caged.

	Single codend		Double codend	
Sample time	Number caged	% mortality	Number caged	% mortality
T_0	480	17.08	484	13.84
T_{24}	476	22.49	480	17.08

At both T_0 and T_{24}, the mortalities to these individuals were greater in the single (17.08 and 22.48%) than in the double (13.84 and 17.08%) codend (Table 2). Because of decay, it was not possible to measure 79 of the dead *M. macleayi* at T_{24}.

In addition to the *a priori* fixed factors of interest (i.e. codend configuration and sample time), environmental and biological parameters that showed the most variability, including the percentage cloud cover and the weights of total catch and jellyfish (Table 1), were chosen for inclusion in the binomial GLMMs to explain mortalities. The most parsimonious model was reduced to significant main effects of sample time ($p = 0.019$), codend configuration ($p = 0.009$), and the weight of jellyfish ($p = 0.0003$). The categorical factors manifested as great overall mortality in the single as in the double codend, and at T_{24} as at T_0 (Table 2). Irrespective of these main effects, mortalities also increased with the quantity of jellyfish present (up to 4.4 and 4.7 kg in one paired deployment of the single and double codends).

Discussion

The low immediate and 24-h mortalities to *M. macleayi* discarded from the conventional, single codend were within the range of earlier estimates for the species (<40%; Macbeth *et al*., 2006; Broadhurst and Uhlmann, 2007; Broadhurst *et al*., in press), confirming their resilience to trawling and discarding. Although preliminary, the results also suggest that such impacts can nevertheless be mitigated, translating to almost a quarter fewer fatalities, simply by compartmentalizing the catch during fishing. The relative effectiveness of this modification can be discussed according to geometric differences in the distribution, and perhaps concomitant pressure, of catches.

A lack of information on the exact geometries of the codends during fishing and their drag coefficients (C_d) precludes quantification of the actual hydrodynamic forces on the accumulated organisms, but it is still possible to postulate relative differences. Specifically, the small diameter of each compartment in the double codend (0.38 m) meant that for most deployments, catches would have distributed laterally to the maximum circumference, then accumulated forwards at approximately the same surface area (0.11 m^2), effectively maintaining the codend in a more or less cylindrical shape (though with a slightly concave bottom; Figure 2). Such a shape would mean that the pressure (expressed as drag divided by the surface area) on individual organisms would be fairly consistent through the entire mass of catch.

In contrast, owing to its cross-sectional area being four times greater, catches in the single codend would have presented a much larger anterior surface area than in the double compartments, but the volumes would not have similarly accumulated across the entire codend, so probably reduced to relatively

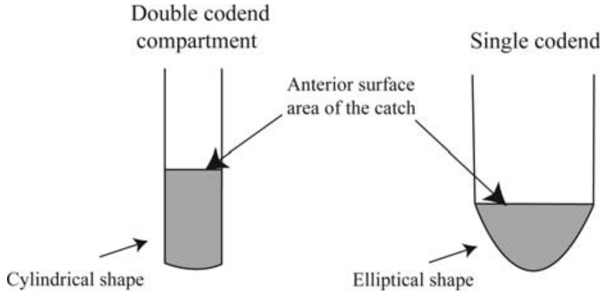

Figure 2. Distribution of catches in the single codend and each compartment of the double codend.

smaller posterior spread (i.e. more elliptical and less cylindrical; Figure 2). The drag would be proportionally greater, and although the anterior pressure would have remained similar to that calculated above (assuming a comparable C_d; O'Neill *et al.*, 2005), there may have been some increase towards the tapered, smaller posterior section of catch. Even slight variations in pressure in the posterior section of this codend may have been sufficient to cause more fatal injuries (such as limb loss and punctured carapaces) to juvenile *M. macleayi*.

In the absence of quantitative data, the potential for differences in pressure between the single and double codends remains speculative, but it is clear that their different geometries would have affected mechanical interactions among *M. macleayi*. Specifically, the proportionally greater surface area and less dense distributions of catches in the single codend (Figure 2) would have exposed more *M. macleayi* to collisions with accumulating conspecifics, and possibly exacerbated their injuries. Conversely, by accumulating forwards more rapidly across the narrower compartments of the double codend (Figure 2), *M. macleayi* effectively would have been immobilized (within perhaps a more-or-less constant pressure) and prevented from colliding and/or abrading with each other and the codend meshes.

Although there were no significant differences in the retained and discarded catches of *M. macleayi* or their sizes between configurations, the narrow length of the double codend nevertheless might have also indirectly reduced mortality by slightly improving selectivity, attributable to a relatively greater encounter probability and more open anterior meshes than in the single codend of larger circumference (Broadhurst and Millar, 2009). More than one-third of the dead *M. macleayi* at T_{24} could not be measured (because of decay), which precluded testing for any impact of size on fatality. However, previous studies have demonstrated a positive correlation for several species (Davis, 2002; Broadhurst *et al.*, 2006). If proportionally more smaller *M. macleayi* escaped from the double codend, then this might have contributed towards the reduction in mortality we observed.

Intuitively, given the differences in codend geometries discussed above, a significant main effect of catch size and/or an interaction with codend configuration on mortality might be expected. However, neither outcome was observed, probably because of the small and generally uniform sizes of catches. For example, during 9 of the 12 deployments, each trawl caught between ~10 and 17 kg; variation that would have been negligible in terms of geometrically affecting each codend. In comparison, during an earlier study to assess the benefits of sorting trawled *M. macleayi* in water for improving their survival in the Hunter River, Broadhurst *et al.* (in press) detected a significant positive correlation between discard mortality and catch weight in the single codend, but this was over weights of 4–47 kg. Although the relationship could be similar for the double codend, given the accumulation of catches forwards at constant surface area, hydrodynamic pressure at the normal towing speed of $1.2\ \mathrm{m\ s^{-1}}$ should remain low, irrespective of catch volume. Of more concern for this codend would be during the period when it is removed from the water and lifted on board, and the catch weight is distributed across the relatively narrow cross-sectional area.

Like Broadhurst *et al.* (2008), we showed that independent of modifications to reduce discard mortality in this fishery, there was a dominant impact of jellyfish that probably can be attributed to their nematocyte discharge and associated toxins. The Nordmøre-grid would have eliminated most of the jellyfish from the trawl (Broadhurst and Kennelly, 1996), but some fragments (up to 5 kg) passed through the bars and mixed with the catches in both codends. Although the few replicate deployments precluded a significant interaction between the weight of jellyfish and gear configuration on mortality, this would be expected with large abundances evoking wide-scale fatalities, despite any geometric benefits of the double codend. The potential for such impacts reiterates the need for effective BRDs to be used (Broadhurst *et al.*, 2006).

The importance of maximizing the escape of unwanted catches via modifications to improve selectivity (such as effective BRDs) during fishing is further supported by a general trend of proportionally fewer mortalities and less damage to escapees than discards (Broadhurst *et al.*, 2006). The latter group also is often more susceptible to other unaccounted fishing mortalities attributable to predation (Broadhurst *et al.*, 2006). Like most shrimp-trawl fisheries (e.g. Lancaster and Frid, 2002), large numbers of birds regularly follow and feed on the discards from Clarence River trawlers. These predators mean that ancillary modifications, such as chutes to return discards unseen into the water (Broadhurst *et al.*, 2008) and/or bird-scaring lines (Løkkeborg, 2002), would be required to reduce the probability of additional mortalities to live *M. macleayi* discarded from the double codend.

Despite the above caveat, the results observed here do support the concept of physically modifying gears to mitigate collateral mortalities during fishing. For penaeid trawling, valid options may not be restricted to compartmentalizing codends within existing configurations, but could extend to the use of smaller, multi-rigged trawls (up to four or five, with the same overall combined headline length). There may also be some utility in examining different netting materials (Bettoli and Scholten, 2006), including knotless vs. knotted mesh for their effectiveness in reducing abrasive injuries. Industry might be encouraged to explore such options if it can be demonstrated that any reduction in mortality and damage concomitantly improves the quality of the retained catches.

Notwithstanding the potential benefits to be derived from pursuing the above options, it is also clear that these should not replace the primary established solutions for mitigating collateral mortality involving appropriate gear selectivity and BRDs. Rather, when used as an ancillary approach along with operational procedures such as short deployments, sorting catches in water, and methods for mitigating predation, they could contribute towards the cumulative reduction in impacts and, ultimately, the improved fate of discards.

Acknowledgements

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