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Cumulative selectivity benefits of increasing mesh size and using escape gaps in Australian *Portunus armatus* traps

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Abstract

The individual and cumulative effects of increasing mesh size (from 56- to 75-mm stretched mesh opening) and installing three escape gaps (36 × 120 mm) in collapsible-netted round traps were assessed to address concerns associated with excessive discarding in an Australian portunid fishery. Compared to conventional traps comprising 56-mm mesh throughout, those with the same mesh size and escape gaps caught significantly fewer (by 54%) undersized blue swimmer crabs, *Portunus armatus* Milne-Edwards and yellowfin bream, *Acanthopagrus australis* Günther (by 64%). Irrespective of escape gaps, simply increasing the mesh size to 75 mm did not significantly affect catches of undersized *P. armatus*, although 87% fewer *A. australis* were retained. Traps with both 75-mm mesh and escape gaps maintained reductions of *A. australis*, but had a clear cumulative effect on *P. armatus* selection, retaining 84% fewer undersized individuals across a larger size at retention. The results support using escape gaps in existing conventional traps, but illustrate the need to configure the minimum legal mesh size to approach the desired target size of *P. armatus* as a precursor to maximising trap selectivity. Larger-meshed traps also require less material (i.e. plastic), which benefits their manufacture and, equally importantly, reduces environmental costs when lost.

KEYWORDS
crustaceans, escape gap, selectivity, trap, undersize

1 | INTRODUCTION

The blue swimmer, *Portunus armatus* Milne-Edwards and giant mud crab, *Scylla serrata* Forsskal, are among Australia's most economically important estuarine crustaceans—particularly throughout the south-eastern state of New South Wales (NSW), where up to 550 and 220 t, respectively, are harvested each year (of which ~55 and 30% are recreationally caught; Broadhurst, Millar & Hughes, 2017, 2018). These species co-occur, although *S. serrata* is euryhaline while *P. armatus* prefers saline areas, which means their targeting is often spatially delineated within and among estuaries (Broadhurst et al., 2017, 2018).

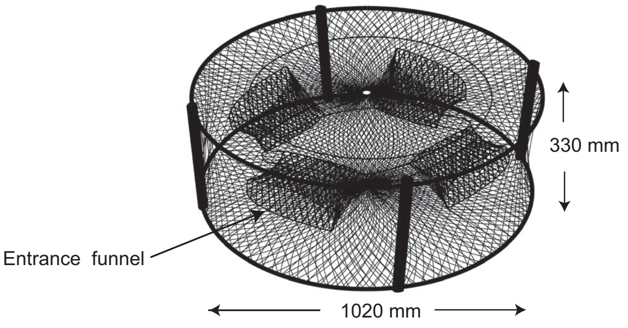
Prior to the early 2000s, and irrespective of the fishing sector or the species, most of the total catches were taken by baited rectangular traps made from wire mesh (square-shaped) with a legal minimum size of 50 mm (Butcher, Leland, Broadhurst, Paterson & Mayer, 2012; Leland, Butcher, Broadhurst, Paterson & Mayer, 2013). The 50-mm squares provided diagonal openings of ~70 mm, which were sufficient to allow the ingress/egress of undersized *P. armatus* (<60 mm carapace length; CL)—the smaller of the two species and perceived to be the more vulnerable to injury and mortality (Leland et al., 2013).

At the turn of the last century, many recreational and commercial fishers started using collapsible-netted round traps comprising a panel of mesh (50–57-mm stretched mesh opening; SMO) tightly secured over a frame of upper and lower steel rings, with four polyvinyl chloride side supports and side entrances, similar to designs used overseas and in other Australian states (Campbell & Sumpton, 2009; Smith & Sumpton, 1989; Figure 1). Due to an anomaly in regulations, a minimum size of 50-mm mesh netting is considered legal because it has a flexible diamond shape, although this orientation is limited to the top and bottom of the trap where the netting is bunched together and tied (allowing the trap to be emptied). All meshes around the trap sides are square-shaped with a minimum diagonal opening of 35 mm and therefore insufficient to allow virtually any *P. armatus* to escape.

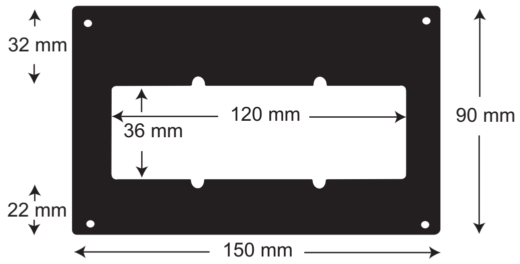
No selectivity curves are available for collapsible-netted round traps, but they are very effective; catching four times as many *P. armatus* as rectangular wire-mesh traps, but often with 50% or more discarded (along with small fish, mostly yellowfin bream, *Acanthopagrus australis* Günther) (Broadhurst et al., 2017; Leland et al., 2013). A recent increase in the legal size of *P. armatus* (to 65 mm CL) for commercial fishers will increase discarding. Ideally, most small *P. armatus* would escape traps while fishing.

In an attempt to improve selection among collapsible-netted round traps for *P. armatus*, Broadhurst et al. (2017) investigated the utility of retro-actively fitted openings (“escape gaps”), and showed that up to three located at the trap base reduced undersized catches by 51–100%. Escape gaps have been demonstrated to be similarly effective in overseas portunid traps (Boutson, Mahasawasde, Mahasawasde, Tunkijjanukij & Arimoto, 2009; Jirapunpipat, Phomikong, Yokota & Watanabe, 2008) and warrant extension and adoption throughout NSW. But, other simple trap modifications might also have utility for improving selectivity, and especially increasing the mesh size to match the minimum target size of *P. armatus*. Based on known morphometric relationships, *P. armatus* with a 65 mm CL have a maximum carapace depth of ~36 mm, which, assuming they could penetrate sideways and force open diamond-shaped meshes, corresponds to a ~75 mm SMO.

(a) Collapsible-netted round trap



(b) Escape gap



(c) Three escape gaps

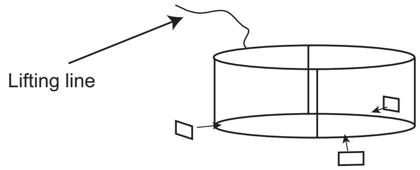


FIGURE 1 Diagrammatic representation of the (a) conventional (control) collapsible-netted round trap and the (b) polypropylene escape gap (with notches and holes for securing to the mesh) with (c) the locations of three inserted into traps

The utility of increasing mesh size has been investigated for collapsible-netted round traps targeting *S. serrata* (≥85 mm CL) albeit with limited success (Broadhurst, Butcher & Cullis, 2014). An SMO of 101 mm was tested but, because of the known confounding effects of entrance type on catches of some portunids (Vazquez-Archdale, Kariyazono & Añasco, 2006), these were maintained at 51 mm SMO to promote ingress of *S. serrata* at the same rate as the conventional traps (Broadhurst et al., 2014). While the larger-meshed traps significantly reduced catches of undersized *S. serrata* and *A. australis*, they were less effective at catching legal-sized *S. serrata*; a result possibly attributed to the species’ behavioural responses to larger mesh around the sides of the trap during initial contact (Broadhurst et al., 2014).

Notwithstanding the above, there often are clear species-specific differences in the catchability of portunids among baited traps, which preclude transferring or rejecting particular modifications designed to improve selection without formal investigation (Broadhurst et al., 2017, 2018; Butcher et al., 2012; Leland et al., 2013). Considering no studies have investigated the effects of different mesh sizes in collapsible-netted round traps used to target *P. armatus*, the main aim here was to compare the utility of traps made from nominal 56- versus 75-mm mesh, and with and without escape gaps, for improving species and size selection.

2 | MATERIALS AND METHODS

The work was done during April and May 2018 using a volunteer commercial fisher targeting *P. armatus* in Wallis Lake (32.27°S, 152.49°E). The fisher was initially provided with 20 collapsible-netted round traps. All traps comprised knotted polyethylene mesh (2.40-mm diameter–Ø twisted twine), suspended between two parallel steel rings (10-mm Ø rod) measuring 1020 mm across, 330 mm high and separated by four polyvinyl chloride pipes, with four 300 × 200 mm semi-closed funnel entrances (Figure 1a).

Ten of the traps were conventional designs made entirely from nominal 56-mm mesh (hereafter, all mesh sizes are SMO), while the remaining ten traps were made from nominal 75-mm mesh throughout (except for their lower entrance funnels, which comprised 56-mm mesh to facilitate *P. armatus* entry). Further, within each of the ten 56- and 75-mm traps, five had three escape gaps, and five did not, providing four different treatment traps, termed: "56-mm"; "56-mm escape-gap"; "75-mm"; and "75-mm escape-gap" traps (Figure 1). Using a local, purpose-built mesh gauge, replicates of each of the traps constructed from the conventional and larger mesh sizes were measured for SMO (n = 10 per trap), and were 55.75 ± 0.14 and 75.39 ± 0.16 mm, respectively.

The escape gaps were made from rectangular polypropylene frames (90 × 150 mm) with internal openings measuring 36 × 120 mm (Figure 1b). Three escape gaps were located (using plastic cable ties) at equal distances apart around the trap bases (Figure 1c). Lifting lines were located between escape gaps and on the same sides, so animals had to escape during fishing and not hauling (Figure 1c). On each of five days (08:00–15:00) in April (6–13) and two days in May (22 and 23), the traps were baited with ~600 g of grey mullet, *Mugil cephalus* L. deployed across conventional fishing areas (~20 ha), and left to fish before being retrieved after "soaks" of either one or two nights.

2.1 | Data collected

The fishing depth and soak time of each trap were recorded, while replicates of bottom water temperature (°C) and salinity were collected across the fishing area during trap retrieval using an Horiba U10 water meter. After trap retrieval, catches were removed and each *P. armatus* was identified as being alive or dead, sexed, measured with Vernier callipers (to the nearest 1 mm) for CL and assessed for moult stage (post-moult or early- or late inter-moult; Broadhurst et al., 2017). The locations and numbers of any new exoskeleton damage defined as missing limbs (chelipeds, pereopods or swimmerets) and/or any carapace trauma were noted. All remaining incidental catches were separated by species and assessed as alive or dead. Any teleosts were measured for total length (TL to the nearest 1 mm) and released.

2.2 | Data analyses

Separate Poisson generalised log-linear mixed models (GLMM) were fitted to the numbers of total, legal- and undersized *P. armatus* and the other abundant, incidental catches. Five fixed effects were considered in all models: "months" (April vs May; in lieu of water temperature and salinity owing to no replicates for individual traps); "soak time"; "mesh size" (56 vs 75 mm); "escape gap" (with vs without); and an interaction between the latter two factors. Random factors included "days" and "individual trap lifts" to allow for extra-Poisson variability. For all GLMMs, a backward selection algorithm was employed with the least significant term removed at each step until all remaining terms were statistically significant at the 5% level. Significant differences for the interaction term were separated using the Benjamini–Hochberg–Yekutieli procedure to control the false discovery rate (FDR).

Size frequencies of *P. armatus* in the three modified traps were compared against those in the 56-mm traps to fit the observed proportions and ratios for each size class via generalised additive modelling (GAM, following Broadhurst et al., 2018). The GAMs assumed a quasi-binomial error distribution for the observed catch proportions of modified traps and confidence intervals around the fitted splines were obtained using the double bootstrap (Millar, 1993; Xu & Millar, 1993). All GLMMs and GAMs were fitted using the glmer function in the lme4 package and the gam function within the mgcv package, respectively, of the freely available R language.

3 | RESULTS

During the five and two fishing days in April and May, replicates of the four trap types were deployed between 32 and 35 times (15.5–54.9 hr soaks, with the same soak-time distribution across the control and all treatment traps) for a total of 137 trap lifts (Table 1). Two 56-mm traps were stolen after the second and third days in April and replaced for the deployments in May. Fishing depths remained similar among all days fished (2.3 ± 0.5 m), but water temperatures and salinities were greater in April (24.7 ± 0.8°C and 30.4 ± 0.2 ppt) than in May (17.6 ± 0.2°C and 25.7 ± 0.5 ppt).

In total, 646 animals comprising eight species were trapped, but *P. armatus* (48–86 mm CL with a total female-to-male ratio of 1:2.9) was dominant with 600 individuals (Table 1). Three *S. serrata* were also caught (all were legal-size; 110–120 mm CL), with the remaining species all "bycatch," including 33 *A. australis* (120–240 mm TL), four tarwine, *Rhabdosargus sarba* Forsskal (120–130 mm TL), three fanbelly leatherjacket, *Monacanthus chinensis* Osbeck (140–300 mm TL), one common toadfish, *Tetractenos hamiltoni* Richardson (180 mm TL), one shortfin eel, *Anguilla australis* Richardson (990 mm TL) and one *Charybdis* sp. (6 mm CL; Table 1).

Only one *A. australis* and one *P. armatus* were observed dead in the traps, providing total immediate species-specific mortalities of 3.0 and 0.2%, respectively. Most *P. armatus* (94%) were late inter-moults (and therefore quite hard), and only 17 had new exoskeleton damage, involving one or two broken chelipeds or swimmerets, mostly (65%) caused during measurement (Table 1). Of the total *P. armatus* caught in the conventional 56-mm traps, 58% were undersize (Table 1).

Analyses of catches were restricted to *P. armatus*, total bycatch and *A. australis* (Table 2). The preferred GLMM for the total catch of *P. armatus* was reduced from five factors to two—mesh size and escape gap—with 16% fewer in the 75- (raw mean ± *SE* of 4.0 ± 0.2/soak) than 56-mm (4.8 ± 0.2/soak) traps, and 40% fewer in all traps with escape gaps (3.3 ± 0.1/soak) than without (5.5 ± 0.2/soak; Tables1 and 2, Figure 2, with interaction means plotted for convenience). These differences in total catch were not greatly affected by legal-sized *P. armatus*, considering the GLMM was reduced to log(soaktime)—which had a positive effect on the catches of these individuals ($p < 0.05$; Table 2, Figure 2). Rather, undersized catches were responsible for most of the differences in *P. armatus* among the two modifications, with the preferred GLMM comprising a main effect of escape gaps and an interaction

TABLE 1 Summary of environmental and biological data collected during replicate deployments of traps made from 56- and 75-mm mesh, and with and without three escape gaps in Wallis Lake, New South Wales, Australia

	56-mm trap	56-mm escape- gap trap	75-mm trap	75-mm escape-gap trap
No. of trap deployments	32	35	35	35
Mean soak time (hr ± *SD*)	26.8 (11.3)	26.95 (11.9)	27.07 (11.9)	26.99 (11.8)
Mean water depth (m ± *SD*)	2.6 (0.6)	2.4 (0.6)	2.1 (0.4)	2.1 (0.4)
Blue swimmer crabs, *Portunus armatus*				
Total no. caught	187	135	181	97
No. per deployment	5.8	3.9	5.2	2.8
Total no. undersized	109	52	104	20
No. undersized per deployment	3.4	1.5	3.0	0.6
Mean CL (±*SD*) of total caught (mm)	63.4 (6.3)	66.5 (4.5)	64.4 (5.9)	68.0 (5.7)
Sex ratio (F:M) of total caught	1:2.3	1:3.4	1:3.3	1:2.7
Moult stage				
Post-moult	2	3	1	0
Early inter-moult	10	5	9	6
Late inter-moult	175	127	171	91
No. with new exoskeleton damage	7	3	6	1
No. of giant mud crabs, *Scylla serrata*	0	0	1	2
Bycatch (no.; size range; and mean ± *SD* TL in mm)				
Yellowfin bream, *Acanthopagrus australis*	22 (100.0–190.0; 149.3 ± 26.0)	9 (110.0–160.0; 135.6 ± 15.1)	2 (240.0–250.0; 240.5 ± 70.7)	0
Common toadfish, *Tetractenos hamiltoni*	0	1 (180)	0	0
Shortfin eel, *Anguilla australis*	0	0	1 (990.0)	0
Fanbelly leatherjacket, *Monacanthus chinensis*	1 (140.0)	0	1 (260.0)	1 (300.0)
Tarwine, *Rhabdosargus sarba*	2 (120.0–120.0; 120.0 ± 0.00)	2 (120.0–130.0; 120.5 ± 7.07)	0	0
Rigid swimming crab, *Charybdis* sp.	0	1 (61.0)	0	0

with mesh size ($p < 0.05$; Table 2, Figure 2). False discovery rate pairwise comparisons for the interaction revealed that compared to the 56-mm traps, simply inserting escape gaps significantly reduced undersize catches (by 56%), while increasing mesh size to 75- mm without escape gaps did not (although the mean was reduced by 13%). When combined, both modifications were the most effective, with the 75-mm escape-gap trap retaining incrementally and significantly fewer undersize *P. armatus* than the 56-mm (mean reduced by 83%), 75-mm (81%) and 56-mm escape-gap (62%) traps (FDR, $p < 0.05$; Figure 2).

The trend in the significant GLMM interaction for undersized *P. armatus* also manifested in GAMs describing relative size-selection curves; among all of which quadratic basis splines had the smallest cross validation and were preferred. The relative selection curves for the 75-mm , 56-mm escape-gap and 75-mm escape-gap traps had a significant effect of CL (GAM, $p < 0.05$) due to lower catchability of *P. armatus* ~<55, 60 and 65 mm, respectively (Figure 3a,c,e). Bootstrap confidence intervals showed the corresponding catch ratios were not significantly different at CLs > 56, 61 and 67 mm, respectively (Figure 3b,d,f).

In contrast to undersized *P. armatus*, variability among the numbers of total bycatch and *A. australis* was best described by GLMMs reduced to the main effects of mesh size and/or escape gaps ($p < 0.05$; Table 2, Figure 4). Compared to traps made from 56-mm mesh, those made from 75-mm mesh caught significantly less total bycatch (by 87%) and *A. australis* (94%), respectively (GLMM, $p < 0.005$; Tables 1 and 2, Figure 4a). The few *A. australis* remaining in the larger mesh traps were all large (Table 1). Irrespective of mesh size, all traps with escape gaps caught significantly fewer *A. australis* (by 64%) than those without (GLMM, $p < 0.005$; Tables 1 and 2, Figure 4b). Escape gaps did not significantly affect the number of total bycatch, but the *p* was 0.06 and the mean was reduced by 54% (Table 2, Figure 4b).

4 | DISCUSSION

This study not only reiterates that the broad utility of simply increasing mesh size in baited crustacean traps (Guillory & Prejean, 1997) or installing escape gaps (Jirapunpipat et al., 2008) for improving

TABLE 2 Summaries of fixed variables considered in mixed effects models for their independence in explaining variability among the numbers of total, legal-sized (≥65-mm CL) and undersized (<65-mm CL) blue swimmer crabs, *Portunus armatus* and total bycatch (non-portunid) and yellowfin bream, *Acanthopagrus australis* in traps with different mesh sizes (56 and 75 mm) and with or without three escape gaps fished across two months

	Portunus armatus				
Variable	Total no.	Legal-sized no.	Undersized no.	No. of total bycatch	No. of *A. australis*
Mesh size (M)	**	–	–	***	***
Escape gap (E)	***	–	***	–	*
M × E	–	–	*	–	–
Month	–	–	–	–	–
Log (soak)	–	*	–	–	–

Notes: Random effects in all models included "days" and "individual" trap lifts.
–*p* > 0.05; **p* < 0.05; ***p* < 0.01; ****p* < 0.001.

selectivity but also, for regional portunid traps, demonstrates their apparent cumulative effects; albeit with species-specific impacts. Such observations can be discussed according to known trap geometry and morphological differences among species and their possible behaviour, and used to recommend trap refinements.

The data here confirm the existing conventional traps are poorly selective for the sizes of *P. armatus* that occur across the fished area, with 58% of their total catch smaller than the recently increased legal size of ≥65 mm CL. Collapsible-netted round traps provide various shapes of mesh openings from square (e.g. around the sides) to diamond (e.g. across the top and bottom), but, irrespective of the location, a 56 mm SMO would only allow *P. armatus* < ~39–45 mm CL to escape (i.e. presuming they orientated sideways; Broadhurst et al., 2017).

In comparison, a forced lateral diamond-mesh opening of 36 mm (to match the CD of a legal-sized *P. armatus*) in the tops of traps made from 75-mm mesh would produce an open length of ~70 mm, close to the recently revised legal size of a *P. armatus* (65 mm CL, or ~70 mm TL), while a square-shaped 75-mm mesh would have maximum internal diagonal openings of 53 mm. Given that the relative selectivity curves show 50% retention at ~51 mm CL for the 75-mm traps and no significant reduction in undersized catches, it is likely that the few small *P. armatus* that escaped did so via the stretched square-shaped meshes around the trap sides, rather than the looser diamond-shaped meshes at the top.

In contrast, based on morphological regressions provided by Broadhurst, Dijkstra, Reid and Gray (2006) *A. australis* and *R. sarba* (80% of the total non-portunid bycatch and both ventrally compressed) up to 150 and 165 mm TL would be able to pass diagonally through a 75-mm mesh that was square-shaped, while fish up to 185 and 191 mm TL could pass through looser diamond-shaped meshes in the top (i.e. mesh perimeter of 150 mm). Most of the *A. australis* in the conventional 56-mm traps were 150–185 mm TL, but these sizes were not caught in the 75-mm trap and so, unlike *P. armatus*, presumably at least some escaped through the tops of the traps.

Irrespective of mesh size, inserting escape gaps also facilitated the escape of some *A. australis*, and presumably by orientating sideways to fit through the 36-mm opening (corresponding to the average maximum height of a 110-mm TL *A. australis*; Broadhurst et al., 2006). This required change in normal swimming orientation might explain why, although escape gaps were effective for fish, larger mesh evoked greater percentage reductions.

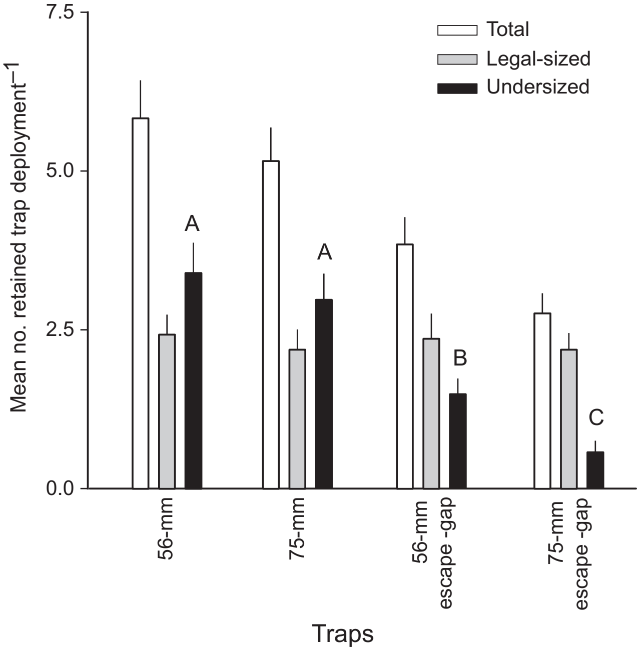


FIGURE 2 Differences in raw mean (+*SE*) numbers of total, legal- and undersized blue swimmer crabs, *Portunus armatus* among traps made from 56- and 75- mm mesh, and with and without three escape gaps. Subscripts above histograms indicate significant differences detected in false discovery rate pairwise tests of the significant interaction between mesh size and escape gap for undersized *P. armatus* ($p < 0.05$)

Unlike *A. australis*, small *P. armatus* would be able to simply move sideways through escape gaps in their normal orientation, and this apparently occurred when escape gaps were located in conventional 56-mm mesh traps, with a 54% reduction in undersized catches. While this rate was at the lower limit (51–100%) previously observed by Broadhurst et al. (2017) for various types of escape gaps, the actual percentage reductions reflect not only the escape-gap design but also the size classes of *P. armatus* present across the fished area. Certainly, the relative selectivity analyses here imply a 50% retention for the 56-mm escape-gap trap (~61 mm) close to the commercial minimum legal size (65 mm CL), and with no significant reduction in legal-sized catches.

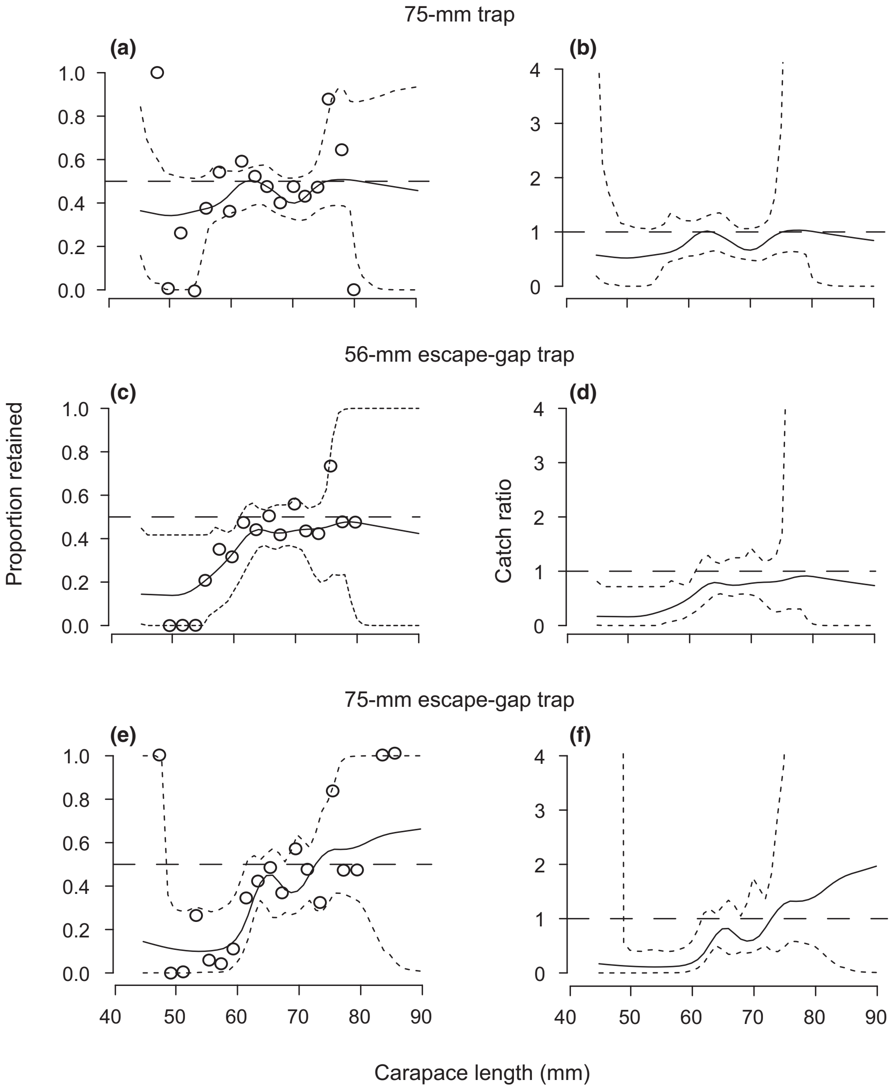


FIGURE 3 Relative proportions and catch ratios at different sizes for blue swimmer crabs, *Portunus armatus* against the 56-mm trap for the (a,b) 75-mm; (c,d); 56-mm escape gap; and (e,f) 75-mm escape-gap traps. The dotted lines show the 95% confidence intervals, while the dashed horizontal lines show the 0.5 and 1.0 proportion and catch ratios and their juncture at size for significant differences

It is also clear that cumulative selectivity benefits associated with installing escape gaps in the 75-mm traps exist; manifesting as a 85% reduction in undersized *P. armatus* from the conventional 56-mm traps (or >1.5 × better than just installing the gaps in a conventional trap). While absence of video precludes definitive statements supporting this cumulative improvement, it could simply reflect more openings across a wider range of sizes (i.e. square-mesh around the sides of the traps and three escape gaps). Because some small *P. armatus* (e.g. <~53 mm CL) could escape through the square-shaped 75-mm mesh, perhaps these were not competing for egress with larger individuals through the escape gaps. Future research using cameras mounted on traps to observe *P. armatus* behaviour within traps may provide evidence of the mechanisms behind the reduction in undersized *P. armatus* when using escape gaps and larger mesh.

The data collected here should facilitate designing more selective traps. In particular, an even larger mesh (e.g. 90 mm SMO) might be introduced around the sides of the trap (i.e. square-shaped) to promote *P. armatus* escape. Depending on *P. armatus* movements in traps, smaller mesh (75 mm) might still be used at the top. Certainly, exploring the limits of simple modifications to mesh size and shape within existing poorly selective net-based fishing gears is considered a more coherent first step towards improving selectivity than attempting to retro-actively fit modifications (Broadhurst, Kennelly & Gray, 2007). Once the minimum appropriate mesh size is determined, other modifications can then be assessed, and given the results here, could have cumulative benefits. An additional benefit of using larger mesh is a reduction in the total quantity of plastic required to build traps. Portunid traps are often lost and with concomitant deleterious environmental implications (Broadhurst & Millar, 2018; Campbell & Sumpton, 2009).

As part of future research, any larger-meshed traps should be tested for their efficiency on the other often spatially separated target species, *S. serrata*, considering Broadhurst et al. (2014) detected a reduction in fishing power for the latter species in traps made from 101-mm mesh. Many commercial and recreational fishers use the same traps for both *P. armatus* and *S. serrata*, and so

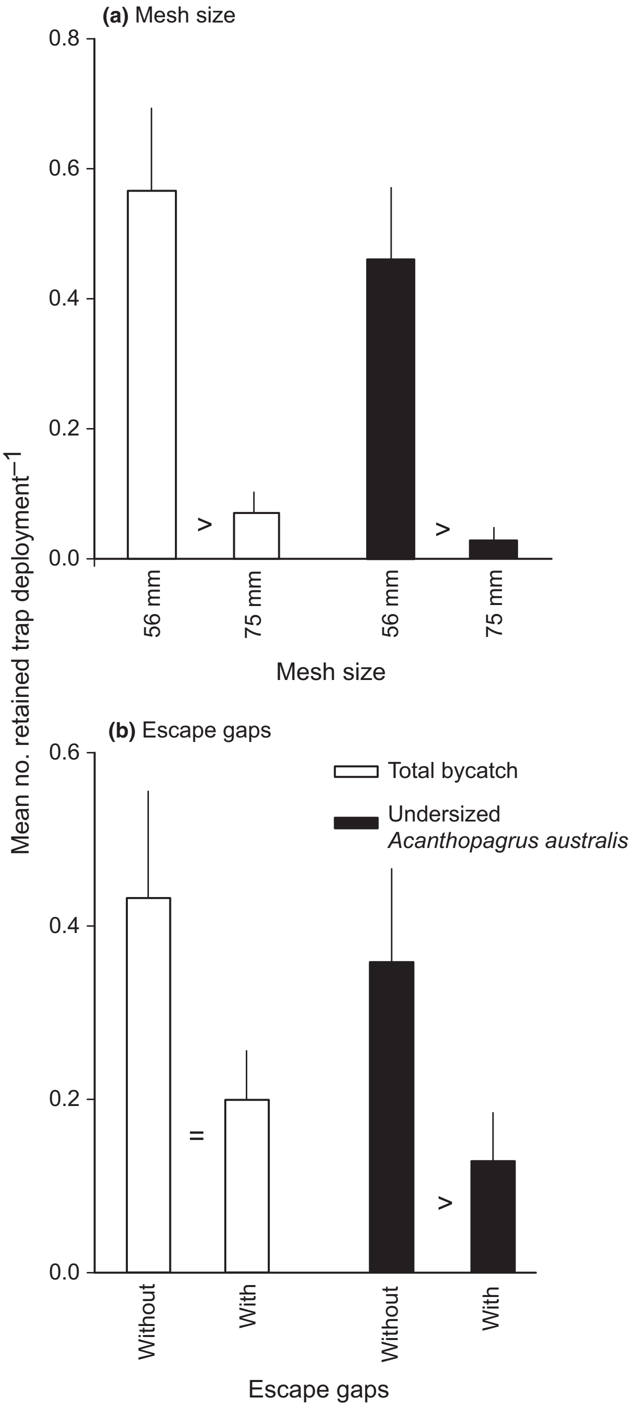


FIGURE 4 Differences in raw mean (+*SE*) numbers of total bycatch and yellowfin bream, *Acanthopagrus australis* in traps: (a) made from 56- or 75-mm mesh; and (b) with and without three escape gaps. <, significant differences (or otherwise, =) detected in generalised log-linear mixed models

modifications need to maintain consistent fishing power for legal catches. Nevertheless, because there is no upper limit for mesh size in traps, the results here imply those fishers wishing to maximise selectively when targeting *P. armatus* should use traps with a mesh size of at least 75 mm and multiple escape gaps.

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