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Optimising mesh size with escape gaps in a dual-species portunid-trap fishery

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ABSTRACT

In south-eastern Australia, the same baited, round traps (comprising 50–57-mm mesh netting) are used to target giant mud, *Scylla serrata* and blue swimmer crabs, *Portunus armatus* in spatially separated fisheries. Both fisheries are characterised by the common, problematic discarding of undersized portunids (< 85 and 65 mm carapace length; CL for *S. serrata* and *P. armatus*) and fish (yellowfin bream, *Acanthopagrus australis*). This poor selectivity was addressed here in two experiments assessing the utility of (1) traps partially or completely covered in larger mesh (91 mm to match the minimum legal size of the smaller *P. armatus*), and then (2) any cumulative benefits of fitting species-specific escape gaps. In experiment 1, there were no differences among catches of legal-sized portunids associated with either partial, or complete trap coverage with larger mesh. Irrespective of mesh coverage, both designs of 91-mm traps also retained significantly fewer (by up to 42%) undersized *P. armatus* and *A. australis*. In experiment 2, replicate traps completely covered in 91-mm mesh were tested against conventional traps comprising 56-mm mesh, and traps with the same mesh sizes, but also three escape gaps configured for either *S. serrata* (46 × 120 mm) or *P. armatus* (36 × 120 mm) (i.e. four treatments in total). All modified traps maintained catches of legal-sized *S. serrata*, and only the 91-mm traps with escape gaps caught fewer legal-sized *P. armatus*. Fewer undersized *S. serrata*, *P. armatus* and *A. australis* (mean catches reduced by up to 49%) were retained in all larger-meshed than small-meshed traps, and in all of those traps with escape gaps (by up to 95%) than without. While there were no significant cumulative benefits of escape gaps in larger-meshed traps (measured by a statistical interaction), there was a trend of fewer unwanted catches overall. These data support configuring portunid traps with mesh sizes matching the morphology of the smallest legal-sized target species. But, simply retroactively fitting escape gaps in existing, smaller-meshed traps will also realize positive selectivity benefits.

1. Introduction

Portunids form the basis of important small-scale fisheries throughout tropical and temperate coastal countries (Vazquez Archdale, Kariyazono, Añasco, 2006; Vazquez Archdale, Añasco, Hiromori, 2006; Jirapunpipat, Phomikong, Yokota, & Watanabe, 2008; Bouston et al., 2009; Butcher, Leland, Broadhurst, Paterson, & Mayer, 2012). In Australia, several species are caught in various recreational and commercial fisheries, although the most valuable and frequently caught are mud crabs (orange mud crab, *Scylla olivacea*, but mostly the giant mud crab, *S. serrata*) and the much smaller blue swimmer crab, *Portunus armatus* (Kaiola et al., 1993). The annual national harvests of these two groups/species are ~1700 and 2500 t p.a., respectively.

Scylla spp. and *P. armatus* have co-occurring distributions, although for many Australian fisheries there is reasonable spatial delineation with *Scylla* spp. restricted to tropical and warm-temperate estuaries/rivers encompassing various salinities, while *P. armatus* has a broader national distribution within saline habitats (Kaiola et al., 1993). These characteristics mean for several jurisdictions there exists sufficient geographical separation to manage mono-specific gears. However, off

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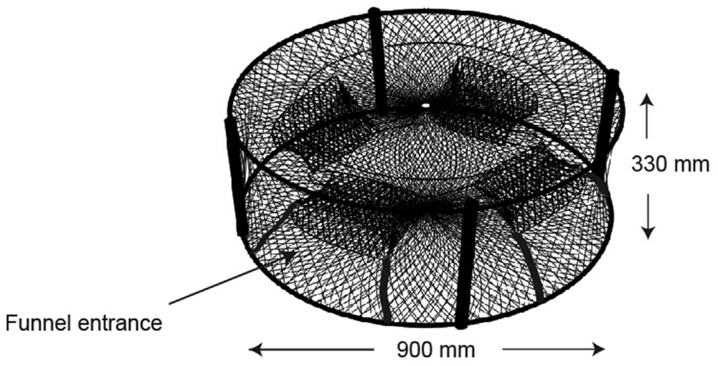
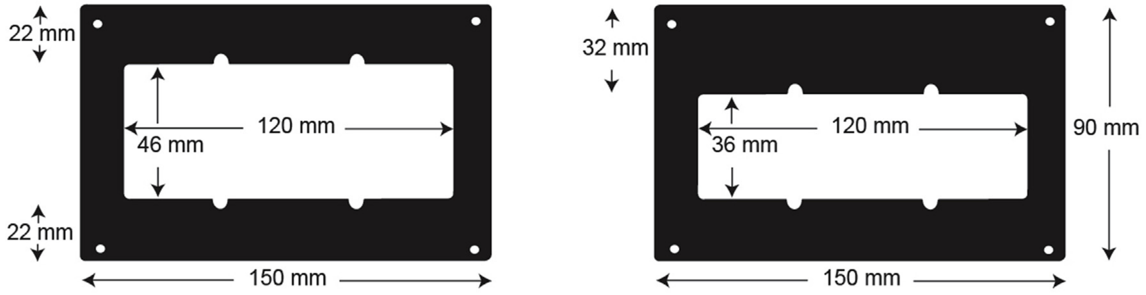
(a) Collapsible netted round trap



(b) *Scylla serrata* escape gap

(c) *Portunus armatus* escape gap



(d) Escape-gap attachment

(e) Three escape gaps

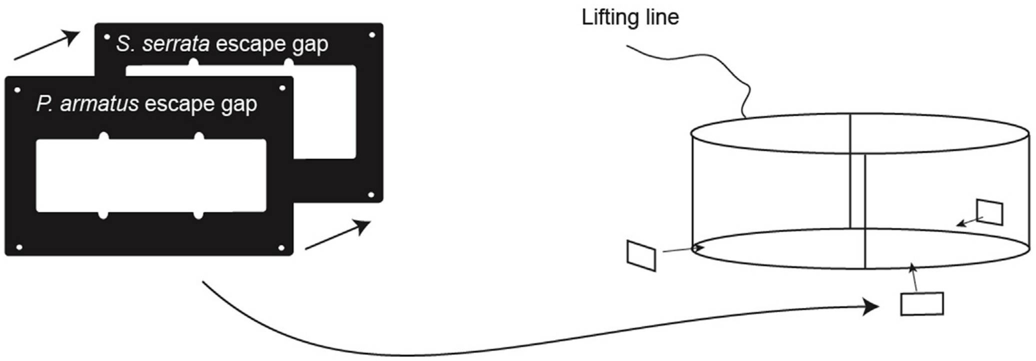


Fig. 1. Diagrammatic representations of the (a) conventional (control) collapsible-netted round trap with the four entrance funnels and polypropylene escape gaps when targeting (b) giant mud crabs, *Scylla serrata* and (c) blue swimmer crabs, *Portunus armatus*, and their attachment configuration (d) when targeting the latter species and (e) in all relevant traps.

south-eastern Australia, including New South Wales (NSW), commercial and recreational fishers historically have used the same baited traps to harvest up to 220 and 500 t of *S. serrata* and *P. armatus* each year (of which ~30 and 50%, respectively are recreationally caught; Henry & Lyle, 2003, p. 188).

Currently, much of the NSW commercial and recreational portunid harvest is taken using collapsible-netted round traps (hereafter ‘round traps’) made from 50 to 57 mm stretched mesh opening (SMO) with four funnel entrances, and similar to traps used in several overseas portunid fisheries (Gabriel, Lange, Dahm, & Wendt, 2005, p. 523, Fig. 1a). Typically, the meshes around the sides of round traps assume a square shape with diagonal openings of ~35–40 mm which preclude the escape of nearly all sizes of either portunid, and are well below the minimum legal size (MLS) of 85-mm carapace length (CL) for *S. serrata* and a proposed increase from 60 to 65 mm CL for *P. armatus*. The small meshes mean large numbers (> 40% of total catches) of both species are discarded (Butcher et al., 2012; Leland, Butcher, Broadhurst, Paterson, & Mayer, 2013). Further, at times round traps also catch teleosts, especially yellowfin bream, *Acanthopagrus australis* (Butcher et al., 2012; Leland et al., 2013; Rotherham, Johnson, Macbeth, & Gray, 2013). Commercial trappers are allowed to retain any fish larger than their MLS, which for *A. australis* is 25 cm total length (TL, corresponding to a maximum height and width of 86 and 32 mm; Broadhurst, Dijkstra, Reid, & Gray, 2006), but recreational trappers must release all fish.

The different MLS for *S. serrata* and *P. armatus* and regulations for discarding fish make it difficult to regulate a round-trap configuration that maximises selectivity throughout NSW. One suggested compromise has involved portunid-specific escape gaps retroactively inserted into existing traps (Rotherham et al., 2013; Grubert & Lee, 2013; Broadhurst, Millar, & Hughes, 2017). Specifically, Broadhurst, Millar, and Hughes (2018a) showed that one to four polypropylene (PP) escape gaps (46 × 120 mm) in the bases of round traps targeting *S. serrata* all reduced catches of undersized conspecifics by up to 93%. Similarly, substituting for three smaller escape gaps (36 × 120 mm) when targeting *P. armatus*, reduced undersized individuals by 77% and *A. australis* by 93% (Broadhurst et al., 2018b). Further, there is evidence that the performance of escape gaps for *P. armatus* improves as catches increase, and presumably owing to overcrowding displacing small conspecifics (Broadhurst et al., 2017). Based on the existing data, the above two sizes of escape gaps are now voluntarily used by some commercial fishers, and can be superimposed into existing round traps according to the target species (Fig. 1b–d). Up to three escape gaps are recommended following Broadhurst et al. (2017).

While escape gaps clearly improve crustacean-trap selectivity (e.g. Treble, Millar, & Walker, 1998; Jirapunpipat et al., 2008), other technical factors can have species-specific utility. These factors include the general trap design or shape (Vazquez Archdale, Añasco, 2006, Vazquez Archdale et al., 2007; Butcher et al., 2012; Leland et al., 2013), funnel-entrance configuration or number (Vazquez Archdale, Anraku, Yamamoto, & Higashitani, 2003; Vazquez Archdale, Kariyazono et al., 2006; Vazquez Archdale, Añasco et al., 2006; Bergshoeff, McKenzie, & Favaro, 2019) and perhaps most importantly, the mesh size/opening (Bellchambers and de Lestand, 2005; Guillory & Prejean, 1997). Intuitively, simply matching mesh size to the MLS of the smallest target species should maximise selection.

The few available data provide some support for increasing mesh size in round traps, with Broadhurst et al. (2019) demonstrating that compared to 56-mm mesh throughout, 75-mm mesh in the sides, and top and bottom of round traps marginally improved selection for *P. armatus*, and had cumulative benefits when three escape gaps were added. However, although increasing mesh size to 101 mm at the same locations in round traps targeting *S. serrata* similarly reduced undersized catches (and also for *A. australis*), there was a concomitant reduction in fishing power for legal-sized *S. serrata*, that was attributed to less ingress through the funnel entrances, and possibly because the larger meshes made it more difficult for *S. serrata* to walk across (Broadhurst, Butcher, & Cullis, 2014).

Such species-specific differences in catches associated with changing mesh size in round traps warrant further assessment to investigate an optimal configuration for targeting both *S. serrata* and *P. armatus*. A mesh size of ~91 mm when stretched square has a diagonal opening of ~64.5 mm which is close to the revised MLS of *P. armatus*. Although the diagonal opening of ~91-mm mesh is still 10 mm smaller than the MLS of *S. serrata*, this might still offer some improved selectivity. Considering the above, here we first sought to assess the utility of increasing mesh size to 91 mm in round traps and associated factors on their selectivity when targeting *S. serrata* or *P. armatus*. But because previous studies showed the potential for confounding effects on the efficiency of even subtle changes to trap entrances (Vazquez Archdale et al., 2003; Vazquez Archdale, Kariyazono et al., 2006; Vazquez Archdale, Añasco et al., 2006; Vazquez Archdale et al., 2007) we assessed the increase in mesh size both throughout the entire trap and also only at the sides and top and bottom (i.e. maintaining small-mesh funnel entrances for portunids to ingress). We then sought to compare the utility of the most appropriate configuration of nominal 91-mm mesh traps against the conventional 56-mm traps, and with and without escape gaps.

2. Materials and methods

2.1. Traps and their deployment in each experiment

Two experiments were consecutively completed between November 2018 and April 2019 (austral summer) at each of two locations—the Corindi River (29°59′ S 153°13′E) targeting *S. serrata* and Wallis Lake (32°19′ S 152°30′E) targeting *P. armatus.* Twenty-five round traps were constructed (Fig. 1a). All traps comprised knotted polyethylene mesh (2.4-mm diameter–Ø twisted twine) stretched between upper and lower steel rings (each 900 mm Ø and made from 10- and 12-mm Ø rod, respectively) that were separated by four polyvinyl chloride support rods (330 mm long; Fig. 1a). Each trap had four evenly distributed 300- × 200-mm semi-closed, funnel entrances (Fig. 1a).

The 25 traps comprised five replicates of a control and four treatments. The control (termed ‘56-mm trap’) represented conventional configurations and was made entirely of nominal 56-mm (SMO) mesh throughout (Fig. 1a). The first treatment trap (‘91-mm trap’) was made entirely of 91-mm mesh (Fig. 1a). The second treatment (‘small-mesh-funnel 91-mm trap’) also had 91-mm mesh, except at the lower funnel entrances (i.e. ~25% of the trap surface area) which were made from 56-mm mesh extending from the base ring to the end of the funnel—-based on the assumption this would facilitate portunid entry (Fig. 1a; Broadhurst et al., 2014). The third and fourth treatments were simply the 56- and 91-mm traps with three escape gaps fitted at the base (termed the ‘56- and 91-mm escape-gap traps’) (Fig. 1b–e). The escape gaps were configured among traps in each estuary according to whether the target was *S. serrata* (i.e. 46 × 120 mm escape gaps in the Corindi River; Fig. 1b) or *P. armatus* (36 × 120 mm escape gaps in Wallis Lake; Fig. 1c). The latter escape gaps were simply superimposed over those used for *S. serrata* (Fig. 1d and e).

In the first experiment, only the 56-mm, 91-mm and small-mesh-funnel 91-mm traps were fished in each estuary. Based on the results (see below), during the second experiment the 56- and 91-mm traps with and without escape gaps (configured for the target species) were fished (i.e. 56-mm vs 56-mm escape-gap vs 91-mm vs 91-mm escape-gap traps) in each estuary. On each of six or seven days, the relevant traps were baited with ~600 g of sea mullet, *Mugil cephalus* that was secured through the eyes to the base by a 200-mm length of wire (1.5 mm Ø) at the centre of the trap and randomly deployed (attached to a single line and surface float) across multiple conventional fishing sites in each estuary, where they were left to fish overnight (for ~16–24 h).

2.2. Data collected

Prior to fishing, ten randomly selected replicate SMOs (nearest 1 mm) were recorded from each trap using a purpose-built gauge. During fishing, the depth and soak time of each trap were recorded, while replicates of bottom water temperature (°C) and salinity were collected across the fishing sites during trap retrieval using an Horiba U10 water meter. After trap retrieval, catches were removed and each portunid identified as alive or dead, sexed, measured with Vernier callipers (to the nearest 1 mm) for their CL and assessed for moult stage following 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 incidental catches were separated by species and assessed as alive or dead. Teleosts were measured for their total length (TL to the nearest 1 mm) and released.

2.3. Statistical methods

Within each experiment (and fishery), separate mixed-effects models were attempted for five traits: the numbers of portunids that were (1) legal- or (2) undersized and (3) the proportion of undersized, (4) the CL of all catches, and (5) the number of undersized *A. australis*. Generalized linear mixed models (GLMMs) were used to analyse the Poisson counts and binomial proportions, while the approximately Gaussian CLs were assessed using linear mixed models (LMMs). All models comprised coherent blocking structures of random factors encompassing some combination of fishing 'Site', 'Day', 'Trap Number' and additionally for CLs, the 'Portunid Number' (Supplementary Information). Fixed effects included 'Soak Time', 'Water Depth' and technical factors were restricted to 'Trap Configuration' (56-mm, 91-mm and small-mesh-funnel 91-mm traps) in experiment 1, and 'Mesh Size' (56 vs 91 mm), 'Escape Gap' (with vs without) and their interaction in experiment 2. Additionally, following Broadhurst et al. (2017), we tested the hypothesis of improved escape of small portunids through larger meshes and/or escape gaps as the 'Total Portunid Number' increased, by investigating this latter factor and its interaction with relevant technical factors in the mixed-effects models fitted to the proportions of undersized portunids and CLs.

All GLMMs and LMMs were fitted in R (R Core Team, 2015) using ASReml-R (Butler, Cullis, Gilmour, Gogel, & Thompson, 2017). However, data for undersized *S. serrata* (both counts and proportions) and *A. australis* were over-dispersed (excessive zeros), so both traits were reanalysed using a zero-inflated GLMM within the glmmTMB package (Brooks et al., 2017). All parameters and estimates reported hereafter pertain to the conditional part of the model, and not the zero-inflated model.

The distributional assumptions underpinning all mixed models were assessed using residual diagnostic plots. Deviance residuals and the corresponding variance heterogeneity were examined for potential misspecification in all GLMMs, and approximate SEs were obtained; but with inherent caution when interpreting such measures from transformed data (Jørgensen and Pederson, 1998).

The statistical significance of the fixed terms was calculated using either approximate Wald *F*- (proportions of undersized portunids and CL) or chi-squared (remaining traits) tests derived via an incremental sum of squares, adjusting for the environmental, biological and technical variables as well as Total Portunid Number (where applicable). Potential interaction terms were tested following their main effects. Relevant estimated means were calculated by averaging across the hypertable constructed from the remaining fixed factors, and taken at the average value of continuous terms (Welham, Cullis, Gogel, Gilmour, & Thompson, 2004). For the LMMs involving Total Portunid Number, the hypertable was constructed using the relative frequency of each catch by treatment combination.

3. Results

The mean (± SE) SMOs of the nominal 56- and 91-mm meshes were 55.8 ± 0.1 mm and 90.7 ± 0.1 mm, respectively. A total of 453 trap deployments were successfully completed during the study, with each experiment involving 30 replicate deployments of the treatments and the control targeting *S. serrata* during six days in the Corindi River and 34 or 35 replicates targeting *P. armatus* during seven days in Wallis Lake (Tables 1 and 2). The fishing conditions remained similar between experiments within estuaries; however the Corindi River had shallower (mean ± SD of 1.7 ± 0.5 m) and warmer (26.7 ± 1.7 °C) water than Wallis Lake (3.1 ± 0.4 m and 22.4 ± 1.0 °C) (Tables 1 and 2). Both estuaries had similar salinities (36.3 ± 1.1 and 36.5 ± 1.3).

3.1. Experiment 1: effects of funnel-entrance mesh size

In total, 365 and 465 *S. serrata* and *P. armatus* were caught and with biases towards males (1:2) and females (1:0.6), respectively (Table 1). Irrespective of their sexes, individuals of both species mostly were intermoults (86 and 92%), and therefore quite hard (Table 1). None of the portunids were dead and very few were damaged (5.7 and 4.1%) during capture, which typically was restricted to a single broken appendage (Table 1). Non-portunid bycatch comprised nine species and 188 individuals, but was dominated by *A. australis* (151) and most (89%) were undersized. All bycatch except for six *A. australis* were alive.

In all mixed-effects models, neither Soak Time nor Water Depth were significant in explaining variability among any traits ($p > 0.05$; Table 3). Further, the key factor of interest, Trap Configuration, was not significant for the numbers of legal- or undersized *S. serrata* or legal-sized *P. armatus* (GLMM, $p > 0.05$), but was for undersized *P. armatus*, with both large-meshed traps similarly retaining up to 42% fewer (difference in predicted mean) individuals than the conventional 56-mm trap (GLMM, $p < 0.001$; Table 3, Fig. 2a and b). These latter differences were also reflected in a significant effect of Trap Configuration on the proportion of undersized *P. armatus*, with up to 14% fewer undersized portunids in the large-meshed traps than the conventional 56-mm trap (LMM, $p < 0.01$; Table 3). Trap Configuration also explained variability in the CL of *P. armatus*, with larger individuals caught in the 91-mm (predicted mean ± SE of 63.91 ± 0.58 mm CL) and small-mesh-funnel 91-mm (63.80 ± 0.55 mm CL) traps than the 56-mm traps (61.14 ± 0.51 mm CL) (LMM, $p < 0.001$; Table 3). By comparison, the only significant effect on the CL of *S. serrata* was the Total Portunid Number, which manifested as a negative relationship with more smaller individuals as numbers increased (LMM, $p < 0.01$; Table 3).

Too few data precluded fitting models for undersized *A. australis* in Wallis Lake (Table 1), but there were sufficient data when targeting *S. serrata* in the Corindi River, with the GLMM limited to a significant main effect of Trap Configuration ($p < 0.001$; Table 3). Compared to the 56-mm traps, both designs of larger-meshed traps similarly retained ~90% fewer undersized *A. australis* (Fig. 2a). Site, Day and Trap Number were sources of most variation in experiment 1 (Supplementary Table S1).

3.2. Experiment 2: effects of increasing mesh size and/or inserting escape gaps

Portunid catches in experiment 2 comprised 439 and 517 *S. serrata* and *P. armatus*, and were biased towards males (1:1.8 and 1:2.1, respectively) and late inter-moults (86 and 85%) (Table 2). Like in experiment 1, very few individuals of either species were damaged (9.5 and 4.0%) and when this occurred it was limited to ~1 broken appendage (Table 2). All portunids were alive except for two *P. armatus* (caught in each of a 56-mm and 56-mm escape-gap trap); one of which was clearly depredated. Nine species were caught as bycatch for a total of 203 individuals. But like for experiment 1, most of this catch was *A. australis* (151), and undersized (89%) (Table 2). Mortalities were restricted to ten *A. australis* and two longtailed catfish, *Euristhmus lepturus*.

The mixed-effects models revealed several catch traits were significantly affected by either Soak Time and/or Water Depth, and all with positive coefficients (GLMM and LMM, $p < 0.05$; Table 4). There were no significant effects among the technical factors of interest (Mesh Size, Escape Gap, and their interaction) on the number of legal-sized *S. seratta* (GLMM, $p > 0.05$, Table 4, Fig. 3a). However, there was a significant Mesh Size × Escape Gap interaction for legal-sized *P. armatus*, with 30–47% fewer retained in the 91-mm escape-gap trap than all three other configurations, which had similar catches (GLMM,

Table 1
Experiment 1: summary of catches among collapsible-netted round traps configured with either all 56-mm or 91-mm mesh, or 91-mm mesh sides and tops, but 56-mm funnel entrances, deployed overnight for six days (19.8–23.9 h soaks) in the Corindi River to target giant mud crabs, *Scylla serrata* and for seven days (15.9–24.2 h) in Wallis Lake to target blue swimmer crabs, *Portunus armatus* during the austral summer 2018/19.

	Scylla serrata			*Portunus armatus*		
	56-mm trap	91-mm trap	Small-mesh-funnel 91-mm trap	56-mm trap	91-mm trap	Small-mesh-funnel 91-mm trap
Total no. of deployments	30	30	30	34	34	35
Mean soak time (h ± SD)	22.4 (0.9)	22.4 (0.9)	22.4 (1.0)	21.8 (1.5)	21.7 (1.7)	21.9 (1.7)
Mean water depth (m ± SD)	1.7 (0.6)	1.6 (0.6)	1.6 (0.4)	3.1 (0.3)	3.1 (0.3)	3.1 (0.3)
Portunids						
Total no. caught	135	125	105	191	129	145
Total no. trap soak^{-1}	4.5	4.2	3.5	5.7	3.8	4.1
Percentage undersized	12.6	16.0	14.3	69.6	58.1	58.6
Mean CL (SD) of total caught (mm)	99.0 (12.8)	98.2 (12.6)	100.7 (11.18)	61.2 (6.7)	64.1 (4.7)	63.9 (4.8)
Sex ratio (F:M) of total caught	1:2.1	1:1.7	1:2.2	1:0.5	1:0.5	1:0.8
Moult stage						
Post-moult	1	2	3	3	6	2
Early inter-moult	30	19	17	15	16	17
Late inter-moult	104	104	85	173	107	126
Percentage exoskeleton damage	5.6	5.6	6.7	1.6	4.7	6.7
If damaged, mean (SD) no. of damaged limbs	1.1 (0.4)	1.1 (0.4)	1.3 (0.8)	1.0 (0.0)	1.3 (0.5)	1.4 (0.7)
Bycatch no.						
Total yellowfin bream, *Acanthopagrus australis*	105	20	14	8	0	0
Legal-sized yellowfin bream	5	8	5	0	0	0
Blackspotted rockcod, *Epinephelus malabaricus*	1	2	3	0	0	0
Diamondfish, *Monodactylus argenteus*	4	0	0	0	0	0
Goldspotted. rockcod, *Epinephelus coioides*	1	0	0	0	0	0
Moses snapper, *Lutjanus russellii*	1	0	0	0	0	0
Longtailed catfish, *Euristhmus lepturus*	0	0	0	1	0	0
Common toadfish, *Tetractenos hamiltoni*	0	0	0	7	0	0
Tarwhine, *Rhabdosargus sarba*	0	0	0	2	0	0
Giant mud crab	Na	Na	Na	1	0	0
Fantail leatherjacket, *Monocanthus chinensis*	0	0	0	1	0	0

Table 2
Experiment 2: summary of catches among collapsible-netted round traps configured with either all 56-mm or 91-mm mesh, with and without escape gaps deployed overnight for six days (20.9–23.8 h soaks) in the Corindi River to target giant mud crabs, *Scylla serrata* and for seven days (19.4–24.1 h) in Wallis Lake to target blue swimmer crabs, *Portunus armatus* during the austral summer 2018/19.

	Scylla serrata				*Portunus armatus*			
	56-mm trap	56-mm escape-gap trap	91-mm trap	91-mm escape-gap trap	56-mm trap	56-mm escape-gap trap	91-mm trap	91-mm escape-gap trap
Total no. of deployments	30	30	30	30	35	35	35	35
Mean soak time (h ± SD)	22.4 (0.7)	22.4 (0.7)	22.3 (0.7)	22.4 (0.8)	21.3 (1.2)	21.4 (1.2)	21.5 (1.2)	21.4 (1.2)
Mean water depth (m ± SD)	1.6 (0.5)	1.6 (0.5)	1.7 (0.5)	1.7 (0.6)	3.1 (0.5)	3.1 (0.6)	3.1 (0.5)	3.1 (0.4)
Portunids								
Total no. caught	142	95	115	87	168	129	151	69
Total no. trap soak^{-1}	4.9	3.2	3.8	2.9	4.8	3.7	4.3	2.0
Percentage undersized	33.0	3.2	21.7	1.1	64.9	42.6	49.0	40.5
Mean CL (SD) of total caught (mm)	93.2 (17.7)	102.1 (9.3)	97.9 (14.2)	104.3 (9.5)	63.3 (4.9)	65.6 (4.6)	65.0 (3.8)	65.8 (4.6)
Sex ratio (F:M) of total caught	1:1.6	1:1.2	1:2.5	1:2.1	1:2.1	1:2.4	1:1.8	1:1.2
Moult stage								
Post-moult	2	1	0	1	7	7	2	2
Early inter-moult	23	25	18	15	29	20	24	22
Late inter-moult	117	69	97	71	132	102	125	45
Percentage exoskeleton damage	12.6	8.4	6.9	9.1	5.4	3.1	3.3	5.8
If damaged, mean (SD) no. of damaged limbs	1.3 (0.8)	0.9 (0.4)	1.0 (0.0)	1.5 (1.5)	2.1 (3.0)	1.3 (0.5)	1.0 (0.0)	1.3 (0.5)
Bycatch no.								
Total yellowfin bream, *Acanthopagrus australis*	81	2	23	2	18	4	2	2
Legal-sized yellowfin bream	9	0	5	2	0	1	0	0
Blackspotted rockcod, *Epinephelus malabaricus*	5	2	6	1	0	0	0	0
Diamondfish, *Monodactylus argenteus*	7	0	0	0	0	0	0	0
Longtailed catfish, *Euristhmus lepturus*	0	0	0	0	5	0	0	0
Tarwhine, *Rhabdosargus sarba*	0	0	0	0	7	2	0	0
Fantail leatherjacket, *Monocanthus chinensis*	0	0	0	0	3	0	1	0
Gloomy octopus, *Octopus tetricus*	0	0	0	0	2	0	0	0
Hairyback swimmer crab, *Charybdis natator*	0	0	0	0	1	0	0	2
Snapper, *Pagrus auratus*	0	0	0	0	8	0	0	0

Table 3

Experiment 1: Summary of mixed effects models assessing the importance of ‘Trap Configuration’ (56-mm, 91-mm and small-mesh-funnel 91-mm traps), ‘Soak Time’ and ‘Water Depth’ on variability among catches and also the importance of ‘Total Portunid Number’ on carapace lengths (CL) and the proportion of undersized portunids, when targeting giant mud crabs, *Scylla serrata* in the Corindi River and blue swimmer crabs, *Portunus armatus* in Wallis Lake during the austral summer 2018/19. Random effects in all models included some combination of ‘Site’, ‘Day’ and ‘Trap Number’, and for CL, an additional random factor of ‘Portunid Number’. The coefficient sign is given in parentheses; Na, not applicable for model.

	Trap Configuration (TC)	Soak Time	Water Depth	Total Portunid Number (TPN)	TC × TPN
Corindi River					
No of legal-sized *S. serrata*	–	–	–	Na	Na
No. of undersized *S. serrata*	–	–	–	Na	Na
Proportion of undersized *S. serrata*	–	–	–	–	–
CL of *S. serrata*	–	–	–	***(-)	–
No. of undersized yellowfin bream, *Acanthopagrus australis*	***	–	–	Na	Na
Wallis Lake					
No of legal-sized *P. armatus*	–	–	–	Na	Na
No. of undersized *P. armatus*	***	–	–	Na	Na
Proportion of undersized *P. armatus*	*	–	–	–	–
CL of *P. armatus*	**	–	–	–	–

–$p > 0.05$; *$p < 0.05$; **$p < 0.01$; ***$p < 0.001$.

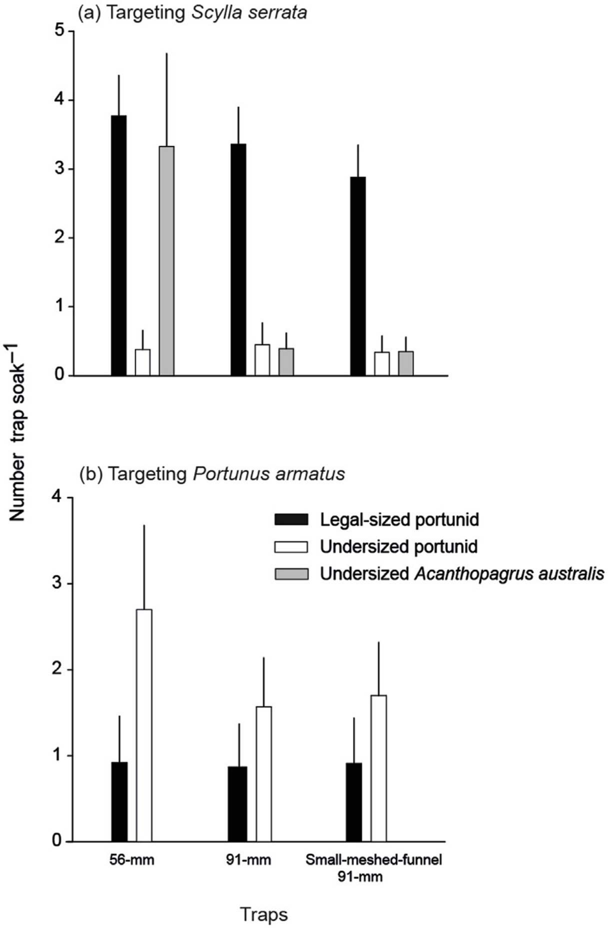


Fig. 2. Differences in predicted mean (+SE) numbers of legal- and undersized portunids and yellowfin bream, *Acanthopagrus australis* when targeting (a) giant mud crabs, *Scylla serrata* and (b) blue swimmer crabs, *Portunus armatus* in experiment 1.

$p < 0.01$; Table 4, Fig. 3b).

Undersized catches of both portunids were significantly and consistently affected by both Mesh Size and Escape Gap (GLMM, $p < 0.05$; Table 4, Fig. 3c and d). Specifically, compared to the 56-mm traps, the larger-mesh traps caught 49 and 38% fewer undersized *S. seratta* and *P. armatus* while, irrespective of mesh size, those traps with escape gaps retained 94 and 55% fewer undersized individuals than those without (Fig. 3c and d). The presence of escape gaps and increasing mesh size significantly reduced the proportions of undersize individuals of both species in traps (GLMM, $p < 0.05$; Table 4). Neither Total Portunid Number nor its interaction with any of the technical factors were significant, and therefore there were no density-dependant influences on the effectiveness of either modification ($p > 0.05$; Table 4).

The dominant effect of escape gaps on catches further presented in the LMMs for CL, with *S. seratta* retained at a significantly smaller mean size in those traps without (98.27 ± 3.68 mm CL) than with escape gaps (104.65 ± 3.69 mm CL) (GLMM, $p < 0.01$; Table 4). By comparison, and like for legal-sized catches, there was a significant Mesh Size × Escape Gap interaction for the CL of *P. armatus*, with a larger mean size of individuals caught in the 91-mm escape-gap (64.7 ± 1.80 mm CL), 56-mm escape-gap (64.13 ± 1.76 mm CL) and 91-mm traps (63.65 ± 1.73 mm), than in the 56-mm trap (61.83 ± 1.74 mm) (LMM, $p < 0.05$; Table 4). The Total Portunid Number also significantly affected the CLs of both species, and again with a negative coefficient (LMM, $p < 0.05$), but no gear interactions ($p > 0.05$; Table 4).

Too few data precluded fitting models for undersized *A. australis* in Wallis Lake (Table 2). However, the GLMM applied to undersized *A. australis* when targeting *S. serrata* in the Corindi River detected main effects of both Mesh Size and Escape Gap ($p < 0.001$; Table 3). Substantially fewer undersized *A. australis* were caught in all 91-mm than 56-mm traps (predicted mean reduced by 75%), and those traps with escape gaps than without escape gaps (reduced by 98%) (GLMM, $p < 0.001$; Table 4, Fig. 2e). Site and Day were the sources of most variation in experiment 2 (Supplementary Table S2).

4. Discussion

This study reiterates that simply increasing lateral openings, via either larger meshes and/or escape gaps, in crustacean traps to match the morphology of the smallest desired sizes of the targeted species can consistently facilitate the escape of small conspecifics and other species, and so dramatically improve selectivity (Guillory & Prejean, 1997; Treble et al., 1998; Vazquez Archdale, Añasco et al., 2006; Jirapunpipat et al., 2008; Bouston et al., 2009; Rotherham et al., 2013; Broadhurst et al., 2014, 2019). The results can be discussed by considering the possible behaviour and known morphology of the targeted portunids with respect to the influences of the three manipulated technical factors (funnel and trap mesh sizes and escape gaps), along with the uncontrolled biological (total catches/trap densities) and environmental (water depth) parameters, and any interactions (or lack thereof).

Table 4

Experiment 2: Summary of mixed effects models assessing the importance of 'Mesh Size' (56 or 91 mm), 'Escape Gaps '(with or without), 'Soak Time' and 'Water Depth' on variability among catches and also the importance of 'Total Portunid Number' (and interactions) on carapace lengths (CL) and the proportion of undersized portunids, when targeting giant mud crabs, *Scylla serrata* in the Corindi River and blue swimmer crabs, *Portunus armatus* in Wallis Lake during the austral summer 2018/19. Random effects in all models included some combination of 'Site', 'Day' and 'Trap Number', and for CL, an additional random factor of 'Portunid Number'. Coefficient signs are given in parentheses; Na, not applicable for model.

Corindi River	Mesh Size (M)	Escape Gap (E)	M × E	Soak Time	Water Depth	Total Portunid Number (TPN)	M × TPN	E × TPN	M × E × TPN
No of legal-sized *S. serrata*	–	–	–	–	–	Na	Na	Na	Na
No. of undersized *S. serrata*	*	***	–	**(+)		Na	Na	Na	Na
Proportion of undersized *S. serrata*	*	***	–	**(+)	*(+)	–	–	–	–
CL of *S. serrata*	–	**	–	*(+)	–	*(-)	–	–	–
No. of undersized yellowfin bream, *Acanthopagrus australis*	***	***	–	–	–	Na	Na	Na	Na
Wallis Lake									
No of legal-sized *P. armatus*	–	–	**	**(+)	**(+)	Na	Na	Na	Na
No. of undersized *P. armatus*	**	***	–	–	–	Na	Na	Na	Na
Proportion of undersized *P. armatus*	*	**	–	–	*(+)	–	–	–	–
CL of *P. armatus*	***	***	*	–	*(+)	*(-)	–	–	–

–$p > 0.05$; *$p < 0.05$; **$p < 0.01$; ***$p < 0.001$.

Ultimately the conclusions based on these data can be used to recommend appropriate modifications to improve round-trap selectivity, both regionally and in other overseas fisheries where similar gears are used.

Of the chronologically manipulated technical factors, the funnel-entrance mesh size had the least impact. Previous studies have shown often dramatic effects of subtle changes to funnel-entrance design on crustacean catches (e.g. Bergshoeff et al., 2019; Yamane & Hiraishi, 2002), including for portunids (e.g. Vazquez Archdale et al., 2003; Vazquez Archdale, Kariyazono et al., 2006; Vazquez Archdale, Añasco et al., 2006; Vazquez Archdale, Santos & Watariguchi, 2019). For example, during an aquaria experiment, Vazquez Archdale, Kariyazono et al. (2006) observed the Asian paddle crab, *Charybdis japonica* exhibited different behaviours during entry to traps made from PE netting, but divergent funnel-entrance designs that manifested as an almost 40% failure rate to enter one type. The poorer efficiency was attributed to the partial entanglement of portunids in funnel meshes and difficulty traversing forward, followed by reversal and escape. While no *in situ* observations were made here, the catches imply legal sizes of both species were able to transverse up the larger meshes (and their more widely spaced mesh bars) and enter the traps.

Conversely, the small-meshed funnel entrances in the 91-mm mesh traps also had no effect on the escape of smaller *P. armatus* and *A. australis*, despite their presence meaning ~25% fewer sufficiently large lateral openings (91-mm meshes) around the trap circumference. Either the small portunids (or *A. australis*) did not attempt to escape from these traps through the entrance-funnel meshes, or when inside the small-mesh-funnel 91-mm traps they were able to move laterally and pass through the few adjacent large meshes between funnel entrances.

The concept of only a few sufficiently large openings around the sides of round traps being required to improve selection is supported by the consistent significant main effect of escape gaps, with three adequate to reduce catches of *S. seratta* and *P. armatus* by 95 and 55%, and irrespective of the mesh size in experiment 2. There were species-specific differences in the relative effectiveness of either increasing mesh size or using escape gaps, with the latter more effective for *S. serrata*, but both equally effective for *P. armatus*. However, this outcome reflected the MLS of each species, with very few undersized *S. serrata* sufficiently small enough to pass though the 91-mm mesh (which was chosen to correspond to the MLS of *P. armatus*).

Nevertheless, of note and unlike Broadhurst et al. (2019) we did not detect a significant cumulative benefit of larger mesh and escape gaps for reducing undersized *P. armatus*, although the mean catches of this species were lowest in the 91-mm escape-gap trap. Specifically, in the earlier study, traps made from 75-mm mesh and with escape gaps cumulatively reduced catches of undersized *P. armatus*; a result simply attributed to more openings across a wider range of *P. armatus* sizes, and so the smallest individuals (< 53 mm CL) could pass through the 75-mm mesh (diagonal opening of 53 mm) and not compete with larger individuals (up to 65 mm CL) at the escape gaps. The same effect was not observed here for undersized *P. armatus*, but the diagonal 91-mm mesh openings (~65 mm) and escape gaps would have allowed the same-sized individuals to escape.

There were also cumulatively fewer numbers of legal-sized *P. armatus* in the larger-meshed traps with escape gaps, but considering the morphology limiting escape above, this result probably reflects less ingress. Other studies have demonstrated similar negative relationships between increasing lateral openings in traps and fishing power for legal-sized crustaceans (Guillory & Prejean, 1997), possibly attributed to changes in tactile or visual stimuli that reduce entry to traps (Broadhurst et al., 2014). It is possible that instead of quickly entering the funnels, some *P. armatus* tried entering the more frequent, larger openings in round traps associated with both 91-mm mesh and escape gaps, and then gave up and moved on. This type of exhaustive behaviour at baited traps was observed for *C. japonica* (Vazquez Archdale et al., 2003; Vazquez Archdale, Kariyazono et al., 2006; Vazquez Archdale, Añasco et al., 2006) and hypothesised to explain a similar reduction in fishing power for *S. serrata* in round traps covered in 101 mm mesh (Broadhurst et al., 2014). Perhaps there are species-specific optimal mesh sizes (or numbers of lateral openings) in baited round traps.

Catches were not only affected by the manipulated technical parameters of interest. As part of the experiments we also sought to determine if the uncontrolled effect of trap catch density (numbers of trapped portunids) affected the performance of changes to mesh size and/or escape gaps. Testing this hypothesis was justified following Broadhurst et al. (2017), who noted the efficiency of escape gaps in traps targeting *P. armatus* increased with their total catches, and presumably because of antagonist conspecific interactions—which often occur among crustaceans in traps effectively stimulating smaller individuals to escape (Everson, Skillman, & Polovina, 1992; Smith & Sumpton, 1989).

Such effects were not observed here for either *P. armatus* or the larger, more aggressive *S. serrata*. But a key difference between studies was relative trap densities. Broadhurst et al. (2017) regularly caught 10–24 *P. armatus* in a single control trap, while the maximum numbers of *S. serrata* and *P. armatus* in control traps here were 9 and 13, respectively, and usually much less. Perhaps maximum (species-specific) thresholds are required to evoke any interactions. Certainly, the potential for density-dependant effects was clear for both species with a

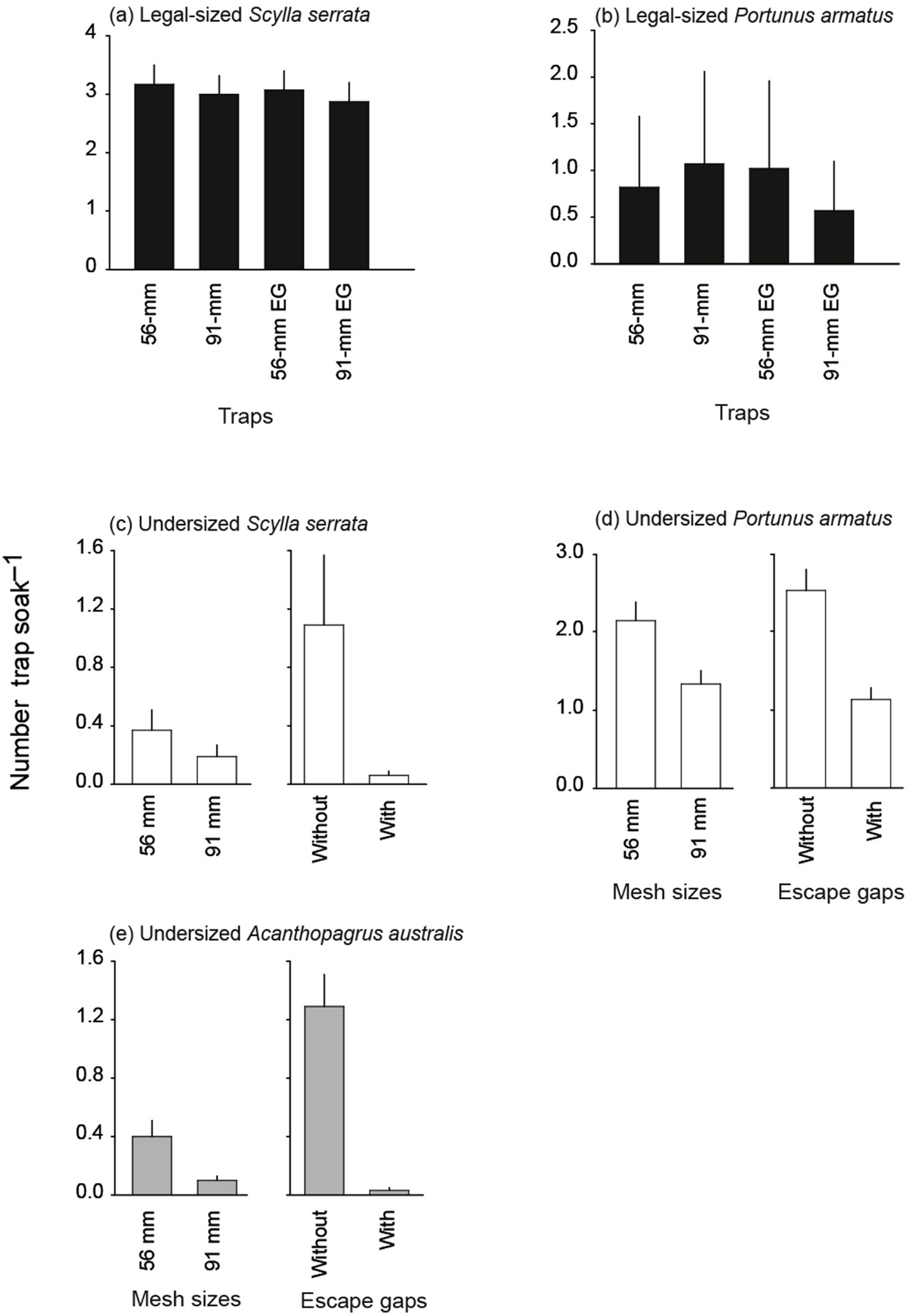


Fig. 3. Differences in predicted mean (+SE) numbers of legal-sized (a) giant mud crabs, *Scylla serrata* and (b) blue swimmer crabs, *Portunus armatus* for each of the four treatment traps (i.e. Mesh Size × Escape Gap (EG) interaction) and undersized (c) *S. serrata*, (d) *P. armatus* and (e) yellowfin bream, *Acanthopagrus australis* for the main effects of Mesh Size and Escape Gap in experiment 2.

significant bias towards smaller individuals in traps as the total numbers increased. Possibly, some larger individuals escaped through the entrance funnels of all traps as the soak progressed. Such escape is common, with Campbell and Sumpton (2009) noting 27% of trapped and tagged *P. armatus* escaped from the entrances of similar traps (without escape gaps) during a ghost-fishing study off eastern Australia.

While not affecting the performances of the tested modifications here, the soak time and fishing depth did positively affected total catches. Considering the discussion above concerning threshold trap densities affecting juvenile egress, possibly by maximising total catches at their upper ranges of influences, soak time and water depth could indirectly interact with either mesh size or escape gaps. More specifically, if the density-dependant effects observed by Broadhurst et al. (2017) and discussed above are maintained, then over larger spatio-temporal scales, escape gaps and/or larger mesh might work better in deeper water or at optimal soak times, simply because more portunids enter traps.

The results here confirm the utility of increasing lateral-mesh openings in crustacean traps to species-specific optimums can dramatically benefit selectivity. While the greater majority of undersized portunids and *A. australis* were released alive with minimal damage, intuitively not catching these animals in the first place would be a coherent management strategy, and not only to minimise mortalities, but also to maximise target catches within the concept of trap saturation (above). Increasing the minimum mesh size from 50 mm to a size approaching 91 mm (with no escape gaps) is a coherent option for both species, and would have negligible cost to fishers as they replace gears. Retroactively inserting inexpensive escape gaps in any trap is also clearly beneficial, although there was an associated reduction in catches of legal-sized *P. armatus* when escape-gaps were inserted into traps covered by 91-mm mesh; an effect not observed for traps comprising 75-mm mesh and escape gaps (Broadhurst et al., 2019).

Based on international work, other modifications to the assessed round traps, including simple changes to the funnel entrance design/shape might also benefit efficiency and/or selectivity, and their assessment warrants ongoing research (Vazquez Archdale, Añasco et al., 2006, Vazquez Archdale et al., 2007, 2019; Bershoeff et al., 2019). In the interim, maximum mesh sizes and escape gaps should be further promoted among commercial and recreational portunid trappers, and not only those fishing in south-eastern Australia, but more broadly in similar overseas fisheries. The widespread use of portunid traps throughout many coastal countries, means that even marginal improvements in selectivity are likely to have considerable cumulative environmental benefits.

Author contribution

All authors contributed to the text in a manner reflecting their order.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.aaf.2019.12.007.

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