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Performance of industry-developed escape gaps in Australian *Portunus pelagicus* traps

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ABSTRACT

In response to concerns over the discarding and subsequent unaccounted fishing mortality of undersized *Portunus pelagicus* (<60-mm carapace length) caused by recent changes to baited traps in south-eastern Australia, commercial fishers voluntarily developed and tested various escape gaps. To facilitate prioritising designs for adoption, data were collected on the relative performances of single and multiple round (64-mm diameter), rectangular (33 × 120 mm) and square (50 × 50 mm) escape gaps across three fishing operations. The immediate mortality and exoskeleton damage among trapped *P. pelagicus* and key contributing factors were also assessed with a view towards predicting impacts among discards. Compared to control traps, those with escape gaps maintained catches of legal-sized *P. pelagicus*, but caught 51–100% fewer undersized individuals. Generally, rectangular escape gaps and especially multiple configurations were the most effective. Irrespective of the escape gap, there was a negative relationship between the proportion of undersized *P. pelagicus* and the total number trapped, which was attributed to intra-specific antagonistic interactions promoting escape (or possibly limiting ingress). Minimal observed damage (mostly appendage loss) among all trapped individuals was positively associated with total catch and less frequent among late inter-moults. While there was no damage bias towards undersized *P. pelagicus* and they only had a 0.2% immediate mortality, escape gaps represent a low-cost option for minimising interactions with unwanted catches throughout the fishery.

1. Introduction

Portunidae comprises more than 500 species globally, with several of the largest targeted in various artisanal, recreational and commercial fisheries (WoRMS Editorial Board, 2016). Two important species groups in Australia are mud (mostly giant mud crab, *Scylla serrata*) and blue swimmer crabs (*Portunus* spp.) (Butcher et al., 2012). Historically, the latter have collectively been grouped as *P. pelagicus*, although Lai et al. (2010) recently revised the classification into four species, (including *P. armatus*, *P. reticulatus*, and *P. segnis*). But for consistency, and because the revision did not assess reproductive compatibility, it remains sufficient to simply report on *P. pelagicus*.

Both *S. serrata* and *P. pelagicus* are targeted by various gears throughout their Australian distributions, although most of the catch comes from baited recreational and commercial traps (Broadhurst et al., 2016). This is especially the case for *P. pelagicus* in southeastern Australia (NSW), where up to ∼300 and 250 t are harvested from estuaries (mostly during the austral summer) by recreational and commercial fishers, respectively (Henry and Lyle, 2003). Virtually all (∼95%) of the commercial catch originates from only five estuaries, and with Wallis Lake the most important.

Until four or five years ago, most commercially trapped *P. pelagicus* in NSW were caught using solid wire-mesh (often with square-shaped openings measuring 50 mm) rectangular traps (Rotherham et al., 2013). More recently, based on their superior catching performance, collapsible, knotted-mesh (50-mm diamond-shaped) round traps have become popular. The same designs are also widely used by many recreational fishers (Leland et al., 2013).

None of the traps used to target *S. serrata* and *P. pelagicus* in NSW are 100% selective for the targeted sizes (current minimum

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legal carapace lengths-CL are 85- and 60-mm, respectively). Poor selectivity, combined with overlapping spatio-temporal distributions of adults and juveniles mean large numbers of undersized portunids are caught and discarded. While previous studies have suggested minimal associated short-term (<72 h) mortality among trapped portunids (Butcher et al., 2012; Leland et al., 2013), concerns remain over sublethal impacts (including limb breakages) to small individuals. Ideally, wherever possible discarding would be avoided.

Previous studies have demonstrated that the selectivity and efficiency of crustacean traps are affected by various technical factors, including when and where they are deployed (Grubert and Lee, 2013), their general design or shape (Smith and Sumpton, 1989; Butcher et al., 2012), entrance type and/or number (Vazquez Archdale et al., 2003, 2006), size of mesh (Guillory and Prejean, 1997; Broadhurst et al., 2014), and especially the use of appropriate escape gaps (Boutson et al., 2009; Rotherham et al., 2013; Broadhurst et al., 2014). Some of these factors have been assessed for Australian portunid traps, including using escape gaps when targeting *S. seratta*. For example, following earlier local (Rotherham et al., 2013) and national (Grubert and Lee, 2013) studies, Broadhurst et al. (2014) demonstrated that collapsible, netted round traps fitted with two rectangular gaps (each 46 × 120 mm) on opposite sides at the base were effective in reducing the catches of undersized *S. seratta* (which have carapace depths < ~46 mm) by 95%, while maintaining legal catches. Ideally, these results will eventually facilitate legislation requiring escape gaps in *S. seratta* traps.

No similar, formal studies have been done with escape gaps in any Australian traps used to target *P. pelagicus*, although overseas studies imply some utility (Boutson et al., 2009). Based on an estimated minimum carapace depth (CD) of ~31–34 mm (Broadhurst et al., 2014) and a total length of ~64 mm for legal-sized *P. pelagic*us (≥60 mm CL), some commercial fishers in Wallis Lake have voluntarily used various shapes and sizes of escape gaps, including circular (~64 mm diameter-Ø) square (50 × 50 mm) and, more recently, rectangular (~33 × 120 mm) configurations (single or multiple), with reportedly positive results. Quantifying the relative utility of these different configurations and any key factors affecting performances is necessary for their prioritisation, promotion and eventual legislation.

Given the above, the primary aim of this work was to compare the relative efficiencies and selectivities of generic, netted round traps fitted with and without different shapes (circular or rectangular) and numbers (up to three) of industry-developed escape gaps fished across multiple operators. A secondary aim was to quantify the immediate mortality or exoskeleton damage among commercially trapped *P. pelagicus*, and if this was biased towards smaller (discarded) individuals.

2. Materials and methods

2.1. Trap configurations

The work was done in Wallis Lake with three volunteer commercial fishers using conventional, collapsible, netted round traps (Fig. 1a). All traps were the same within and between each fishing operation and comprised knotted polyethylene mesh (nominal stretched mesh opening-SMO of ~52 mm), suspended between two parallel steel rings (10-mm diameter-Ø rod) measuring ~0.9 m across and separated by four polyvinyl pipes (~0.3 m apart), with four 0.30 × 0.20 m semi-closed funnel entrances (Fig. 1a).

Five types of escape gaps with combinations of between one and three in each trap were used among the three fishers (Table 1; Fig. 1b–h). The first escape gap (termed 'spectacle') was used by all three fishers and comprised two adjacent nominal 64-mm internal Ø circular rings (made from 0.4-mm Ø stainless rod) (Fig. 1e). Each fisher had replicate traps comprising either one or three spectacle escape gaps (Fig. 1b and d). The second escape gap ('wire-rectangular') was used by two fishers and made from 0.4-mm Ø stainless rod welded into a rectangle (internal dimensions of 33 × 120 mm), and with either one or three in replicate traps (Fig. 1b, d and f). The remaining escape gaps were unique to each of two fishers and included: a clear poly(methyl methacrylate) (PMMA) rectangle (internal and external dimensions of 33 × 120 mm and 53 × 139 mm, respectively and termed 'PMMA-rectangular') that was fished either as a single or double treatment (Fig. 1b, c and g); a single panel of six adjacent polyvinyl chloride (PVC) squares (50 × 50 mm) termed 'PVC-mesh' (Fig. 1h); and a single panel of six adjacent metal rods (3-mm Ø) squares (50 × 50 mm) termed 'wire-mesh' (Fig. 1h). All escape gaps were located at the base of the traps and, for the multiple treatments, at equal distances apart (Fig. 1c and d).

During three to six consecutive days, the fishers deployed up to 60 traps day^{-1} including various replicates of the different treatments and up to 15 traps without any escape gaps as controls. On each day of fishing (08:00–13:00 h), all traps were baited with ~600 g of either luderick, *Girella tricuspidata* or sea mullet, *Mugil cephalus* and deployed across conventional fishing areas for up to three days.

2.2. 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 quality meter. After retrieval, catches were removed from the traps and various data collected following two general approaches dictated by logistics. At a broad level for every trap, *P. pelagicus* were assessed as alive or dead before being sexed and separated into legal- and undersized categories, with the latter discarded. Any non-portunid bycatch was also discarded after being identified and counted, with any fish measured for their total length (TL) to the nearest 1 mm.

More detailed data were collected for individually numbered replicate traps fitted with the more frequently used single and triple spectacle and wire-rectangular escape gaps, and a similar number of assigned controls. For all of these traps, in addition to the legal status and sex, each *P. pelagicus* was measured with Vernier callipers (to the nearest 1 mm) for CL and assessed for moult stage following Hay et al. (2005): (i) post-moult: clean and highly flexible shell, no wear on chelae; (ii) early inter-moult: moderately flexible shell and some wear on chelae; or (iii) late inter-moult: little or no flex in shell, and/or large, considerable wear on chelae. The locations and numbers of any new exoskeleton damage, defined as missing limbs (chelipeds, pereopods or swimmerets) or egg clusters (if relevant) and/or any carapace trauma were also noted.

2.3. Data analyses

In addition to the random variability in the catch of each trap lift, the experimental design included other sources of randomness due to potential variability between fishers, days and sites. Failure to incorporate these additional sources of variability in the statistical analysis results in pseudo-replication (Hurlbert, 1984) and can lead to invalid inference. Here, all relevant sources of variability were explicitly incorporated by using mixed models that included fishers, days, sites and individual trap lifts as random effects (Millar and Anderson, 2004).

Separate generalized log-linear mixed models (GLMM) were fitted to the total, legal- and undersized numbers of *P. pelagicus*, while

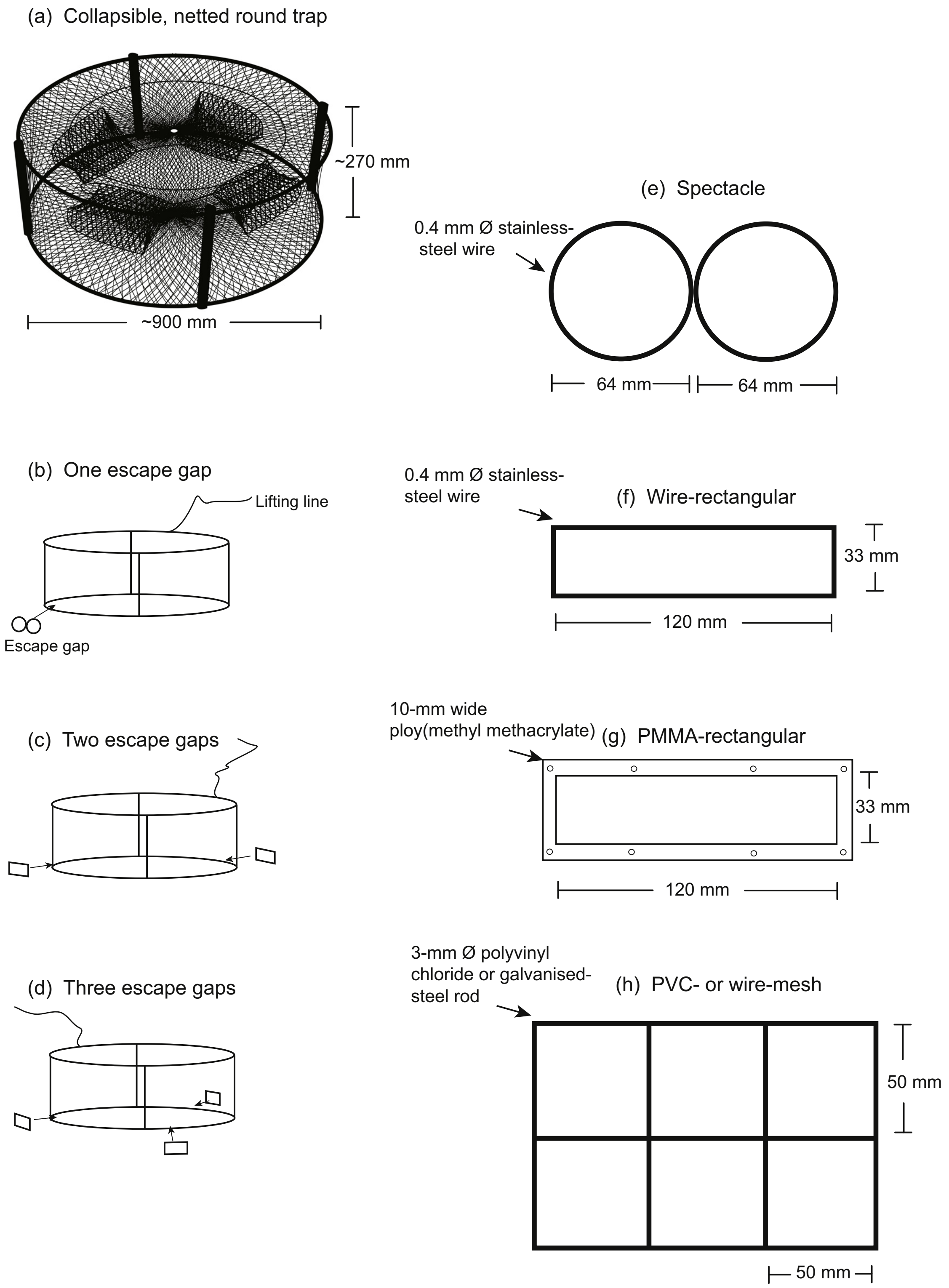


Fig. 1. Diagrammatic representation of (a) conventional (control) collapsible netted round trap, with (b) one (c) two and (d) three escape gaps and the (e) spectacle, (f) wire-rectangular, (g) PMMA-rectangular and (h) PVC- or wire-mesh escape gaps.

a binomial GLMM was fitted to their sex ratio. Fixed effects initially considered for inclusion in the GLMMs for catches were 'soak time', 'depth' and 'trap configuration'; however there was no relationship between soak time and catches and so this term was excluded. Water temperature and salinity were not considered because replicates were unavailable for individual traps during their entire soak. The GLMM testing the hypothesis of no difference in sex ratios for *P. pelagicus* had the fixed main effects of trap configuration and 'legal status' and their interaction.

For the more detailed data describing *P. pelagicus* in some controls and traps with the spectacle and wire-rectangular escape gaps, we fitted a linear mixed model (LMM) to the approximately Gaussian CL data, and binomial GLMMs to the presence or absence of new damage among total and undersized *P. pelagics*. Where appro-

Table 1

Summaries of traps with and without (control) various escape gaps deployed by three fishers during 3–14 days (08:00–13:00 h and for 17–72 h) and numbers of total and undersized trapped blue swimmer crabs, *Portunus pelagicus* and bycatch (excludes all mud crabs, *Scylla serrata*) caught.

Traps	No. of fishers	No. of days fishing	No. of trap deployments	*P. pelagicus*		No. of bycatch
				Total no.	Undersized no.	
Control	3	14	130	989	254	16
One spectacle	3	14	80	587	75	12
Three spectacle	3	14	76	495	69	3
One wire-rectangular	2	10	41	237	34	4
Three wire-rectangular	2	10	39	213	16	1
One PPM-rectangular	1	6	54	348	33	9
Two PPM-rectangular	1	6	9	52	0	1
One wire-mesh	1	6	51	355	49	3
One PVC-mesh	1	3	14	109	9	1

priate, these models had the fixed effects of trap configuration, depth, 'sex', 'moult stage' and 'CL' (for GLMMs describing damage only). Additionally, because inspection of the more detailed catch data implied improved performance of escape gaps with increasing total catch, we tested the associated hypothesis in a separate GLMM with the trap configuration × total catch interaction as the main effect, and the proportion of trapped undersized *P. pelagicus* as the response variable.

For all models, 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. All fits were obtained using the lmer function in the lme4 package of the freely available R language.

3. Results

In total, 493 trap deployments were completed (17–72 h soaks; mean ± SE of 28.7 ± 12.1 h) by the three fishers in depths of 1–4 m (2.7 ± 0.7 m) during 14 consecutive days across the same area (all within ~20 ha) in the Lake (Table 1). Salinity remained fairly constant (34.7 ± 0.8) during fishing, but water temperature varied from 12.4 to 18.9 °C (16.2 ± 1.7 °C).

Catches comprised 3391 *P. pelagicus* (Table 1; with a female-to-male ratio of 1:0.4), 13 *S. seratta* (all legal-sized; >80-mm CL) and 50 other individuals (bycatch) from eight species: yellowfin bream, *Acanthopagrus australis* (6–15 cm TL); rough leatherjacket, *Scobinichthys granulatus* (12–29 cm TL); ocean leatherjacket, *Nelusetta ayraud* (19–23 cm TL); fantail leatherjacket, *Monocanthus chinensis* (22–29 cm TL); shovelnose ray, *Aptychotrema rostrata* (60–80 cm TL); pink snapper, *Chrysophrys auratus* (13–18 cm TL); tarwhine, *Rhabdosargus sarba* (13 cm TL); mangrove swimming crab, *Thalamita crenata*; and octopus, *Octopus*, sp. Insufficient data precluded analysing non-portunid bycatch, but there was a trend of fewer in traps with escape gaps (Table 1). All bycatch were released alive, and only five *P. pelagicus* (four legal- and one undersized) were dead during trap clearance, providing an immediate discard mortality of 0.2%.

3.1. Catch comparisons among traps

The preferred GLMMs explaining variation among the numbers of total (0–27 individuals trap^{-1}), legal (0–26 individuals trap^{-1}) and undersized *P. pelagicus* (0–12 individuals trap^{-1}) all had their fixed effects reduced to trap configuration, but a significant difference was only observed for undersized individuals ($p < 0.001$; Table 2, Fig. 2). Specifically, compared to the control, all traps with escape gaps maintained legal catches, but caught 51–100% fewer undersized *P. pelagicus*, and with trends of sightly greater reductions among multiple vs single configurations of the same design, and especially by the three wire- and two PMMA-rectangular escape gaps (Fig. 2). These reductions remained independent of sex, with no evidence of differences in the overall ratios of either legal (1:0.4) or undersized *P. pelagicus* (1:1.1) among trap configurations (GLMM, $p > 0.05$; Table 2).

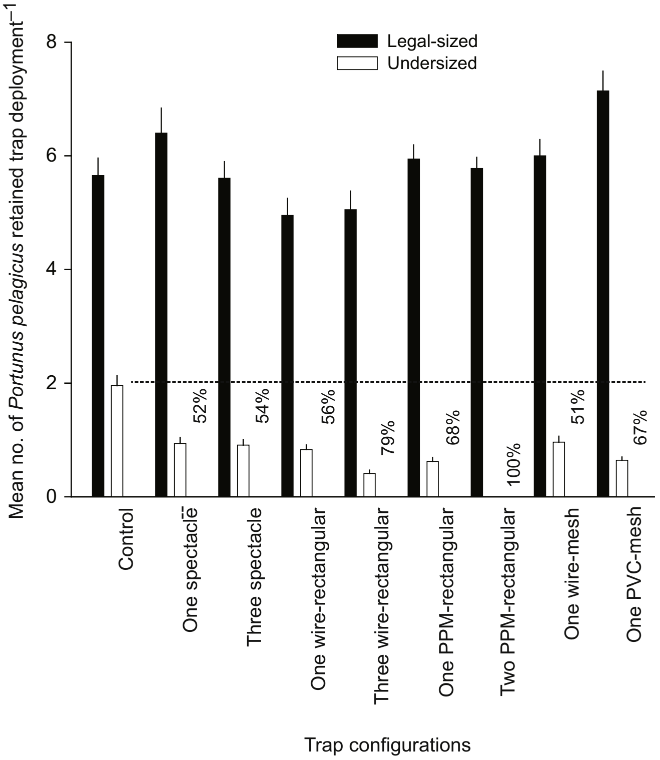


Fig. 2. Differences (+SE) in raw numbers of legal- and undersized *Portunus pelagicus* catches in traps with escape gaps and controls (no escape gaps). The percentage reductions from the control are indicated above histograms for the significant effect of trap configuration on undersized individuals (GLMM, $p < 0.001$).

The escape of undersized *P. pelagicus* from traps with escape gaps manifested in a significant main effect of CL, with controls having smaller individuals (observed mean ± SE of 64.57 ± 0.26 mm CL) than traps with either the one (66.25 ± 0.25 mm CL) or three (65.78 ± 0.25 mm CL) spectacle or one (65.73 ± 0.43 mm CL) or three (66.54 ± 0.37 mm CL) wire-rectangular escape gaps (GLMM, $p < 0.001$; Table 2). Irrespective of trap configuration, male *P. pelagicus* were smaller than females, while late inter-moults were larger than post- and early inter-moults combined (LMM, $p < 0.001$; Table 2).

The proportion of undersized *P. pelagicus* in the spectacle and wire-rectangular traps was also significantly affected by the total catch (GLMM, $p < 0.01$; Table 2, Fig. 3). Specifically, fewer undersized individuals where caught in all four escape-gap traps as total catch increased (GLMM, $p < 0.01$; Fig. 3a), but no similar relation-

Table 2
Summaries of variables considered in mixed effects models for their independence in explaining variability among the numbers of total, legal- and undersized blue swimmer crabs, *Portunus pelagicus*, their proportion undersized and sex ratio across all traps, and the carapace length (CL) and new damage among total and undersized individuals caught only in the control traps and those with the spectacle and wire-rectangular escape gaps. Random effects in all models included 'fishers', 'days', 'sites' and 'individual' trap lifts.

Variables	Numbers of			Proportion			New damage	
	total	legal-sized	undersized	undersized	Sex ratio	CL	total	undersized
Trap configuration (T)	–	–	***	NA	–	***	–	–
Depth	–	–	–	NA	NA	–	NA	NA
Total *P. Pelagicus* (TP)	NA	NA	NA	NA	NA	NA	***	–
T × TP	NA	NA	NA	**	NA	NA	NA	NA
Legal status (LS)	NA	NA	NA	NA	***	NA	NA	NA
T × LS	NA	NA	NA	NA	–	NA	NA	NA
CL	NA	NA	NA	NA	NA	NA	–	–
Sex	NA	NA	NA	NA	NA	NA	–	–
Moult stage	NA	NA	NA	NA	NA	NA	*	–

NA, term not applicable/considered in model.
$-p > 0.05$.
* $p < 0.05$
** $p < 0.01$.
*** $p < 0.001$.

ship occurred within the designated control traps (GLMM, $p > 0.05$; Fig. 3b).

3.2. *Damage among trapped* P. pelagicus

New damage was observed among 200 of 2192 assessed *P. pelagicus* and typically was limited to one or two broken chelipeds, pereopods or swimmerets (mean number ± SE of 1.40 ± 0.08). Only six ovigerous females were caught, and only one had obvious damage to the egg cluster. Most *P. pelagicus* were late (75%) or early (23%) inter-moults, with only 2% post moults.

Neither CL nor trap configuration significantly affected the presence of new damage among total or undersized *P. pelagicus* (GLMM, $p > 0.05$; Table 2). Rather, both of the preferred GLMMs were reduced to the fixed effects of moult stage and total catch (Table 2). However, while the direction of differences were similar, these effects were only significant for total *P. pelagicus*, with the log-odds of damage increasing by 0.094 for each additional individual caught and 0.420 lower among late inter-moults than post- or early inter-moults combined (GLMM, $p < 0.05$; Table 2).

4. Discussion

This study further supports the effectiveness of generic escape gaps for improving the size and species selectivity of traps targeting portunids (Boutson et al., 2009; Grubert and Lee, 2013; Rotherham et al., 2013; Broadhurst et al., 2014) and crustaceans in general (Treble et al., 1998; Hart and Crowder, 2011). Perhaps more importantly, by assessing various escape gaps across different combinations and fishing operations we have nevertheless shown that performances can vary considerably. Such variation can be discussed according to likely important biological (e.g. *P. pelagicus* behaviour and morphology) and technical (e.g. escape-gap shape and material) factors, and ultimately used to recommend appropriate configurations for ongoing extension among industry.

Visual observations of *P. pelagicus* behaviour and responses to baited traps are limited (Smith and Sumpton, 1989) but when considered with studies done on other portunids, there are broad, consistent trends (Vazquez Archdale et al., 2003, 2006). More specifically, these studies have shown that portunids typically approach baited traps from down current (by walking) and, after contacting the sides, push their claws through the meshes in attempts to gain access to the food. Failing to penetrate, they either move away, or laterally around the trap perimeter until encountering the entrances (which supports having multiple entrances in a round shape). During an aquaria study, Smith and Sumpton (1989) observed that approximately one-third of *P. pelagicus* were able to enter round traps (two entrances, but no escape gaps) on their first attempt, but the majority took five minutes or longer and most gave up after three failed attempts.

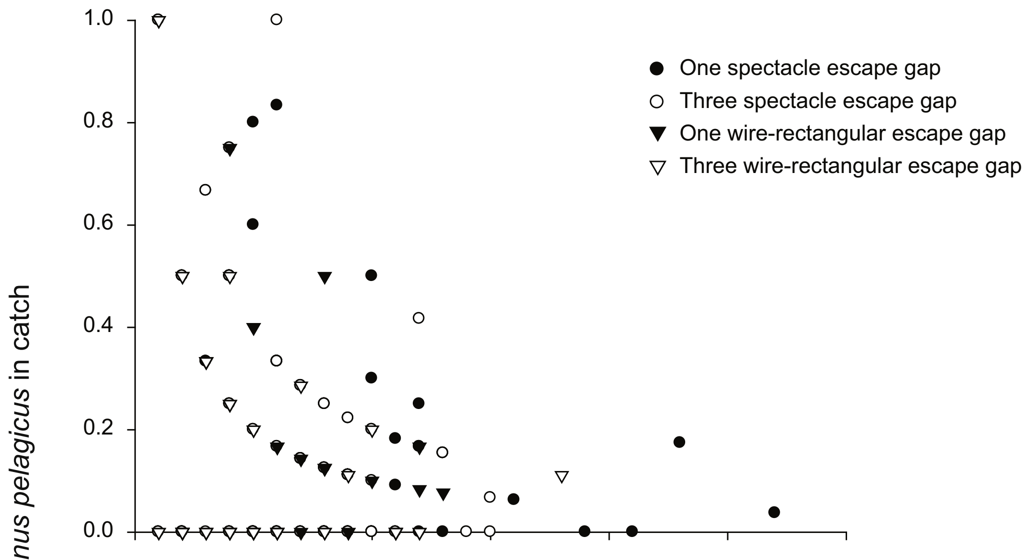
It is also established that once inside a trap, like other crustaceans (Miller, 1979; Frusher and Hoenig, 2001; Ihde et al., 2006), *P. pelagicus* can display antagonistic behaviour towards each other (Smith and Sumpton, 1989). For example, Smith and Sumpton (1989) noted that some trapped *P. pelagicus* attempted to defend the bait and funnel entrances against newcomers or less dominant individuals in the trap causing these to retreat—often by swimming (if in the trap), or backing out (if in the trap entrance).

Any similar behaviour among trapped *P. pelagicus* in Wallis Lake might explain why multiple escape gaps (irrespective of design) appeared to be slightly more efficient than single configurations. Intuitively, simply placing more escape gaps around the trap perimeter could increase the possibility of random encounters by any smaller *P. pelagicus* attempting to escape aggressive conspecifics.

Intra-specific interactions might also explain why the total number of individuals in the trap affected both the exoskeleton damage among all *P. pelagicus* and the escape of juveniles (i.e. from the one and three spectacle and wire-rectangular escape gaps). Potentially, as catch density increased, any associated antagonistic behaviour resulted in greater (although still minimal) limb loss and smaller *P. pelagicus* were forced to seek openings irrespective of their design or number. Further, presumably damage was exacerbated among post and early inter-moults (which compromise variable proportions of total catches during the summer fishing season; Broadhurst et al., 2016) because of their softer exoskeletons, although the overall impacts were minimal (one or two broken appendages).

Notwithstanding the consistent positive relationship between total catch and the escape of undersized *P. pelagicus*, like in previous studies on the same (Boutson et al., 2009) and other crustaceans (Brown, 1982) there was evidence that escape-gap shape was somewhat important, which possibly reflected *P. pelagicus* escape mechanisms and/or morphology. For example, although there were marginal differences, across the tested conditions rectangular escape gaps (and especially multiple configurations) were associated with greater reductions in catches of undersized individuals than spectacles. Because undersized *P. pelagicus* have carapace

(a) Traps with escape gaps



(b) Control

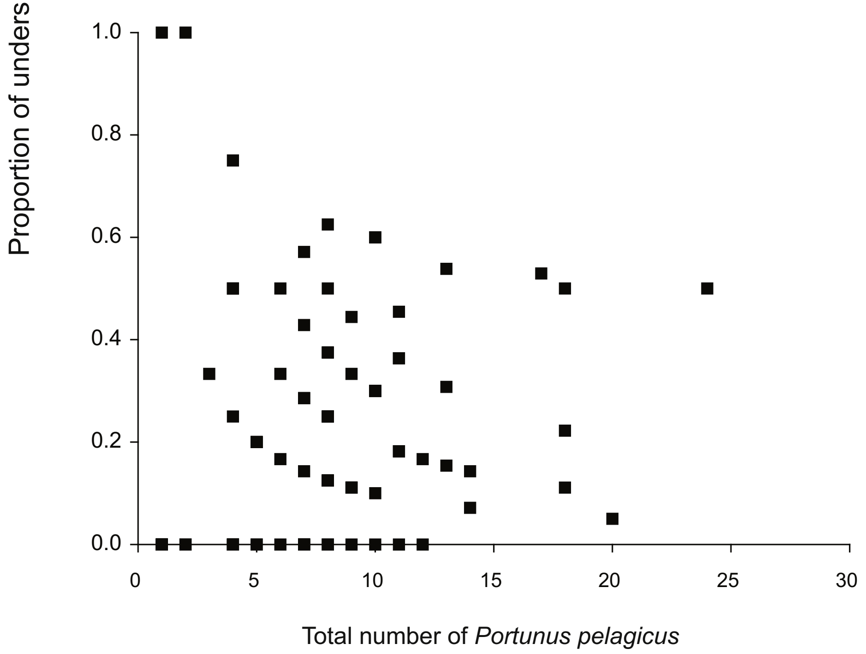


Fig. 3. Scatter plots of the proportion of undersized *Portunus pelagicus* in the catch vs total numbers in (a) traps with either one or three spectacle, or one or three wire-rectangular escape gaps (with data for the four treatment traps designated by different symbols) and (b) the control (with no escape gaps).

depths and widths < ~33 and ~130 mm (Broadhurst et al., 2014) most would have to orientate sideways (i.e. to present their narrowest dimension) to pass through a spectacle escape gap. This would also be the case for most *P. pelagicus* escaping from the 50-mm squares (which were 70-mm on the diagonal). But for the wider wire- or PMMA-rectangular escape gaps, at least some undersized *P. pelagicus* would also have the option of passing through closer to widthways (and possibly backwards), which might have increased the probability of successful escape.

Further, because escaping *P. pelagicus* would need to secure their legs around the edge of an escape gap, by having a wider perimeter, the PMMA-rectangular design might have facilitated escape, contributing towards its apparently better performance. It is also possible that, owing to their relatively greater flexibility than the wire-rectangular escape gaps, the PMMA material allowed more small *P. pelagicus* to slide through, especially considering the majority were quite hard (i.e. late inter-moults). Notwithstanding this result, the number of PMMA-rectangular escape-gap deployments was low, and further data are required to investigate the effectiveness of this configuration.

The performance of the square PVC- and wire-mesh escape gaps (made from 50 × 50 mm mesh), imply that considerably fewer small *P. pelagicus* would be caught by relevant older-style commercial wire-mesh traps than the more recently introduced, collapsible netted round traps. While most of the undersized individuals observed here incurred minimal damage (and certainly no more than their larger conspecifics) and presumably survive if immediately released, ideally they would avoid capture. It is clear that escape gaps, and especially multiple, rectangular designs, in collapsible netted round traps are a simple solution for promoting such an outcome.

Considering the results here, future research might benefit from refinements to escape gaps via different materials (e.g. PMMA vs wire) and/or for rectangular designs, perhaps increases in length (e.g. >130 mm) to exceed the maximum carapace width of undersized *P. pelagicus*. Nevertheless, there seems no reason why the multiple use of escape gaps should not be promoted among commercial fishers. Further, considering the annual recreational (mostly trapped) harvest of *P. pelagicus* can exceed commercial catches in NSW, concomitantly mandated escape gaps could assist in reducing the unwanted mortality of undersized individuals across the entire exploited stock.

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