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Reducing the marine debris of recreational hoop nets in south-eastern Australia

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ABSTRACT

Alternative configurations of Australian recreational portunid hoop nets were investigated to address debris and selectivity issues. Four treatment nets (all comprising 152-mm polyamide–PA mesh) were assessed that differed in their twine (conventional multifilament vs new multi-monofilament) and fishing configuration (conventional conical vs inverted shapes). The conical multifilament design lost means (\pm SEs) of 130.6 ± 23.1 and 5.3 ± 1.2 mm of twine 3-h soak⁻¹ when used to target *Scylla serrata* and *Portunus pelagicus*. Inverting this hoop net significantly reduced legal-sized catches (by up to 70%) and with greater twine loss ($\times 5$) when targeting *P. pelagicus*. Conversely, both multi-monofilament configurations maintained legal catches of *S. serrata* and *P. pelagicus*, but lost 78 and 95% less twine than the conical multifilament design. Using multi-monofilament hoop nets could reduce PA debris by thousands of m p.a. in south-eastern Australia, without affecting targeted catches. Further, a lower fishing height of inverted multi-monofilament nets might reduce non-portunid bycatch.

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1. Introduction

Portunids form the basis of important recreational fisheries throughout Australia, with >9 million individuals caught each year (Henry and Lyle, 2003). Catches mostly comprise *Scylla serrata* and up to four *Portunus* congeners (until recently collectively grouped as *P. pelagicus*; Lai et al., 2010), and typically are taken from various baited traps—the regulations describing which vary among states (Campbell and Sumpton, 2009; Butcher et al., 2012; Broadhurst et al., 2015, 2016, 2017).

Like for trap fisheries globally, most of the recreational traps targeting Australian portunids are considered to have benign environmental impacts, including negligible benthic contact and low bycatch (Butcher et al., 2012; Leland et al., 2013; Uhlmann and Broadhurst, 2015). However, one method that has raised ongoing concerns is the conical hoop net (or so-called ‘witches hat’) which is an inexpensive and popular baited recreational gear fished throughout south-eastern Australia (New South Wales, NSW) (Butcher et al., 2012; Leland et al., 2013; Broadhurst et al., 2015, 2016).

Hoop nets are regulated by a minimum 13 mm stretched mesh opening (SMO), base diameter (<1.25 m) and height (<1 m), with up to four permitted per recreational fisher in >100 estuaries (typically

deployed either diurnally for <6 h, or overnight) to catch daily personal quotas of 10 *P. pelagicus* (≥ 60 mm carapace length; CL) and five *S. serrata* (≥ 85 mm CL) (Butcher et al., 2012; Broadhurst et al., 2015). While the limited technical regulations imply a plethora of designs, virtually all hoop nets comprise a rectangular panel of ~152-mm mesh made from thin (~<0.9 mm diameter- \emptyset) multifilament polyamide (PA) twine sewn into a cylinder 30 meshes in circumference and 6 or 7 meshes long (Fig. 1a). One end of the cylinder is attached to a ~750-mm \emptyset galvanized steel ring, while the other is laced tightly together and secured immediately below a small float, resulting in a conical net that entangles catches as they attempt to access a centrally located bait (Fig. 1b).

Owing to their construction and catching method, there are two key environmental issues associated with hoop nets. First, they often are damaged and with some twine lost as marine debris (and potentially entangled around escaping organism). For example, Leland et al. (2013) observed that hoop nets (~0.7 mm \emptyset multifilament PA twine) set for up to 24 h to target *P. pelagicus* had between 1 and 11 meshes damaged (i.e. broken bars) per net. Damage rates among the same hoop nets targeting *S. serrata* were worse at 7–12 meshes per net (Butcher et al., 2012). Further, after 24 h, nearly 60% of hoop nets used to target both species had >20 meshes broken and were considered unusable (Broadhurst et al., 2015, 2016). No quantitative data are available describing the amount of twine lost during mesh breakage in hoop nets, but it is widely acknowledged that such debris has pervasive negative consequences for the environment (e.g. Derraik, 2002; Chiappone et al., 2005; Rochman et al., 2015).

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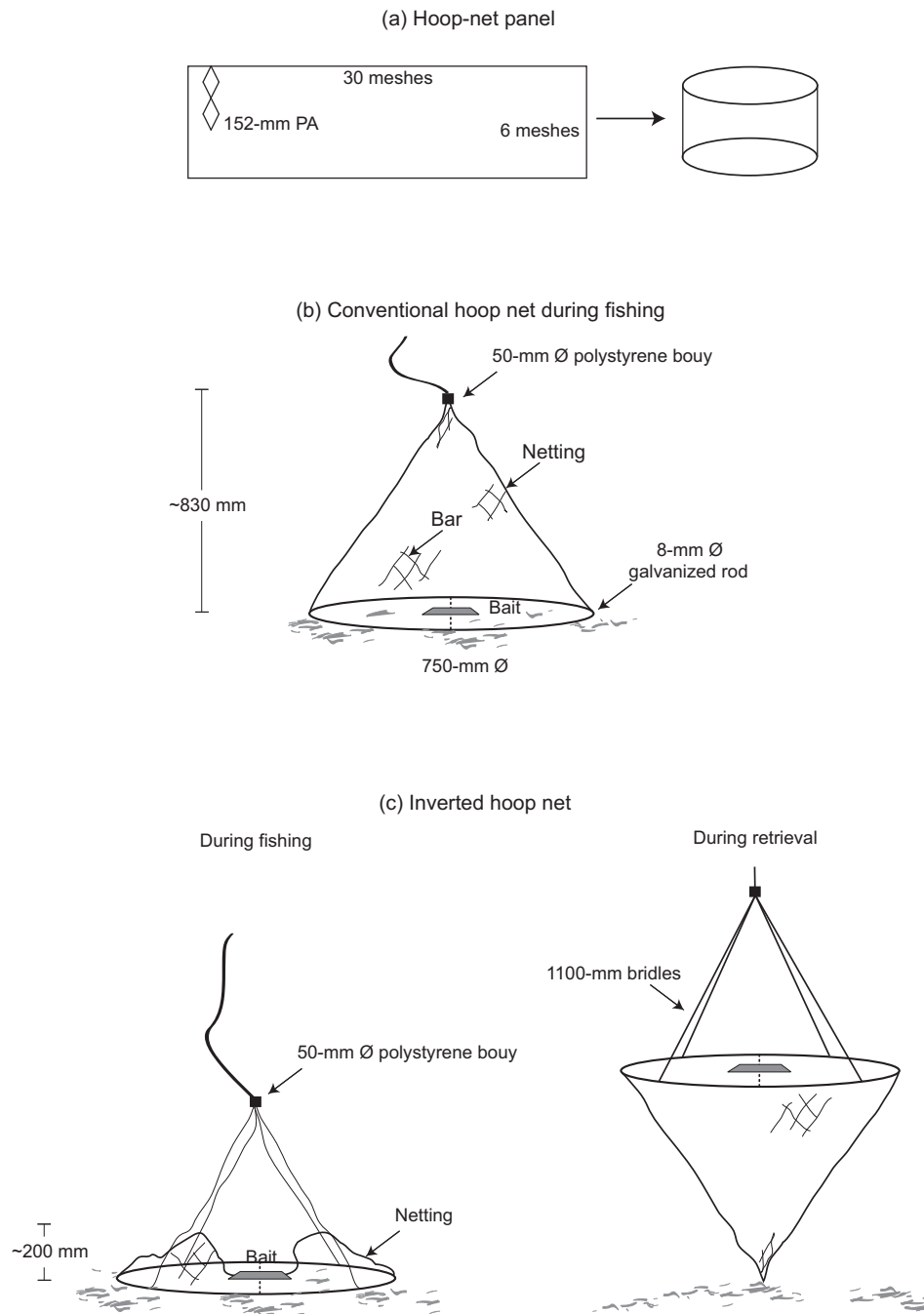


Fig. 1. Diagrammatic representation of (a) the panel used to construct hoop nets, (b) a conventional conical hoop net during fishing, and (c) an inverted hoop net during fishing and retrieval.

A second environmental issue is that hoop nets are neither 100% size nor species selective and so, in addition to undersize or excessive (beyond personal daily quotas) portunids, unwanted fish and, on very rare occasions at some locations, green turtles *Chelonia mydas* are caught. Non-portunid bycatch can asphyxiate, while portunids can lose limbs during disentanglement. Although short-term mortalities to portunids are low (Butcher et al., 2012; Leland et al., 2013), there remain potential negative implications for longer-term survival (Uhlmann et al., 2009).

Beyond prohibiting hoop nets (for which there is considerable resistance by recreational fishers, which typically comprises >800,000 participants), the stated environmental issues might be ameliorated via subtle design changes, and possibly (i) stronger materials and/or (ii) lower vertical orientation in the water column (to spatially limit catches of fish and turtles). Previous studies have shown that these parameters

can influence the efficiency and selectivity of other entangling gears (e.g. gill and trammel nets; Gray et al., 2005; Uhlmann and Broadhurst, 2015), but few data are available for hoop nets used in NSW (but see Broadhurst et al., 2015).

In the only relevant published study, Broadhurst et al. (2015) identified a negative relationship between mesh damage and the multifilament PA twine Ø (0.5–0.8 mm), although the thickest conventional twine was still readily damaged and caught fewer *P. pelagicus*—potentially owing to reduced elasticity. An alternative approach might be to assess other, stronger materials that maintain elasticity (and therefore catches), but with less propensity to break. One option is relatively thicker multifilament twine, which is readily available and used by professional gill netters in south-eastern Australia to catch various species, including *P. pelagicus* (Gray et al., 2005).

In terms of regulating vertical orientation, Broadhurst et al. (2015) showed that simply lowering the height of hoop nets via fewer meshes (in length and therefore total area) reduced mesh damage, but with a proportional reduction in efficiency for portunids. Recently, in an attempt to maintain efficiency but reduce bycatches (and especially *C. mydas*), recreational fishers were requested to remove the float and invert hoop nets so they assume a lower vertical height and the bait is on top of, rather than underneath the netting—similar to other crustacean entangling gears (e.g. Kennelly and Craig, 1989) (Fig. 1c). No quantitative data are available describing the effects of such a configuration on catches or net damage.

Considering the above, our aims in this study were to compare the relative durabilities (in terms of quantifying broken meshes and lost material to the environment) and catches (including damage to portunids) of four treatment hoop nets rigged in conical and inverted configurations and made from either the thickest conventionally used/available multifilament or alternative multi-monofilament PA twines. Specifically, we sought to compare conical (i) multifilament and (ii) multi-monofilament; and inverted (iii) multifilament and (iv) multi-monofilament hoop nets.

2. Methods

2.1. Treatment hoop nets

Each hoop net comprised an identical cylindrical netting panel made from nominal 152-mm SMO measuring 30 meshes in circumference (transverse direction–T) and 6 meshes in length (normal direction–N) for a total twine length of ~54 m, with one end attached to a 750-mm diameter (Ø) galvanized-steel rod (8-mm Ø) base and the other end secured together in an apex (Fig. 1). All hoop nets had a bait bag (0.25 × 0.20 m wire-mesh–10 × 10 mm) secured to a 4-mm Ø polyethylene (PE) line stretched across each side of the rod base (Fig. 1). The only material difference among all hoop nets was the type of polyamide (PA) twine, which was either (i) ~0.9-mm Ø multifilament PA (sold as 210-denier, 15-ply twine) or (ii) ~1.2-mm Ø multi-monofilament (sold as 1.5 gauge × 20 strand). Initially, ~100 hoop nets of each twine type were purchased (multifilament twine) or constructed (multi-monofilament).

Within each twine treatment, half of the hoop nets were rigged in their normal conical configuration with a 50-mm Ø polystyrene (PS) buoy secured at the net apex and retrieval line attached (Fig. 1b). The remaining hoop nets in each treatment were inverted (i.e. rotated 180°) and had a retrieval bridle attached to their frame with a 50-mm Ø PS buoy at the top (to keep the bridle clear of the netting; Fig. 1c). The four treatments described above were labelled as the: conical (i) multifilament and (ii) multi-monofilament; and inverted (iii) multifilament and (iv) multi-monofilament hoop nets.

Prior to fishing, replicates of each hoop-net treatment were placed into an 800-L tank and observed for their orientation/geometry. Three replicates of each treatment hoop net were also randomly selected and had 10 meshes measured for stretched mesh opening (SMO) using Vernier callipers (to the nearest 0.1 mm) and twine diameter using an Olympus Bi WF10X microscope graticule with a 10/100 mm micrometer disc (under ×4 magnification). Ten meshes were then cut from each hoop net and the twines soaked in seawater before the knots were undone and ~150-mm lengths were tested for wet tensile line strengths using a Chatillon DFX-100 (Brooklyn, NY, USA) digital force gauge attached to an adjustable Chatillon LTCM-100-EU motorised tester. The force gauge was rated to 500 N (accurate to 2.5 N) and recorded the strength at the point of maximum elasticity or separation within a specified sensitivity of 0.1 N. The speed of the tester was set at 100 mm min⁻¹ (with a speed accuracy of 15 mm min⁻¹).

2.2. Fishing and data collected

Replicates of all four treatments were concomitantly and repeatedly fished (for up to nine days and nights) following conventional recreational diel practices at each of two locations: the Corindi River (29° 58'S, 153°13'E) to target *S. serrata*; and at Wallis Lake (32° 19'S, 152° 30'E) to target *P. pelagicus* between January and April 2016. On each day/night of fishing in each estuary (8:50–14:51 h) up to ten replicate hoop nets of each of the four treatments were baited with ~600 g of chopped mullet, *Mugil cephalus* and deployed at least 50 m apart (to ensure independence) for between two and five hours. Following the diurnal deployments, the replicated treatments were rebaited, redeployed (16:00–20:00 h) and nocturnally fished until the following morning over soaks of between 15 and 19 h.

During all deployments, the depth fished (m), water temperature (°C) and salinity were recorded. After each hoop net was retrieved, all catches were immediately removed, counted by species and assessed for mortality. Any fish were measured for total length (TL to the nearest 0.1 cm) before being discarded. Portunids were emptied into the boat (with the time taken to remove each recorded) before being sexed, measured with Vernier callipers (to the nearest 0.1 cm) for carapace length (CL) and their moult stage determined 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, significant wear on chelae.

The locations and numbers of missing and/or damaged limbs (cheli-peds, pereopods or swimmerets) and/or any carapace damage and when this occurred (i.e. during the deployment, removal from traps or measuring) were assessed for each portunid. Any ovigerous females were noted and assessed for damage to their egg cluster (to the nearest 5% missing). *Scylla serrata* were t-bar tagged while *P. pelagicus* had a numbered cable tie secured around the mid-section of the merus on their left chelae (following Broadhurst et al., 2016) and all were released at their capture site.

After catches were recorded, each hoop net was assessed for the number of broken and/or missing bars (i.e. four bars comprise one mesh; Fig. 1b) and the cumulative length of missing twine (to the nearest 0.1 cm). Those hoop nets with fewer than 10 broken and/or missing bars were processed onboard and repaired prior to redeployment (as per common recreational fishing practices). Hoop nets with >10 broken and/or missing bars were considered unusable and were labelled, stored and eventually assessed in the laboratory as above.

2.3. Statistical analyses

A linear mixed model (LMM) was used to assess for differences in the SMOs and twine diameters and strengths of the treatment hoop nets. In these analyses, the 'twine material' and 'hoop-net orientation' and their interaction were fixed, while the individual nets were treatment as random.

All data collected during fishing were separately analysed within each experiment using mixed models to test the null hypothesis of no differences between treatment hoop nets for the key variables of interest, and with 'days', 'sites' (within estuaries) and/or 'specified deployments' fitted as random effects. Generalized linear mixed models (GLMMs) were fitted to the Poisson traits of (i) portunid catches (total, legal and undersize) and (ii) broken and/or missing bars among hoop nets, and the binomial (ii) presence or absence of new damage to portunids. Linear mixed models (LMM) were applied to the approximately Gaussian (iii) CL of portunids, and (iv) the length of twine missing from hoop nets.

All models considered the fixed effects of 'hoop net' (conventional and inverted multifilament and multi-monofilament nets) and 'diel deployment' (nocturnal vs diurnal). Although not of primary interest, additional fixed-effect covariates including water 'depth', 'temperature'

and 'salinity' were also considered (because previously these have been shown to affect portunid catchability; Butcher et al., 2012). Where relevant for GLMMs, soak times were log-transformed and coded as an offset for the confounding diurnal differences, while in the LMMs any relevant raw data were log-transformed and standardised for soak time. For each analysis, 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 categorical fixed factors of interest were separated using the Benjamini-Hochberg-Yekutieli procedure to control the false discovery rate (FDR; Benjamini and Yekutieli, 2001) and the raw means (\pm SE) standardised to 3 h soak¹ and graphed. All model fits were obtained using the lmer function in the lme4 package of the freely available R language.

3. Results

Totals of 18–53 replicates of each treatment hoop net were purchased (multifilament) or constructed (multi-monofilament) and used during 89–142 deployments to target each portunid (Table 1). There were no significant differences in mesh size between multifilament and multi-monofilament hoop-nets with predicted mean (\pm SE) SMOs of 152.31 ± 0.68 and 152.58 ± 0.68 mm, respectively (LMM, $p > 0.05$). However, the twine diameter and wet breaking strength of the multifilament (0.91 ± 0.01 mm and 16.93 ± 0.56 kgf) were both significantly less (by 26 and 43%) than those of the multi-monofilament (1.23 ± 0.01 mm and 29.47 ± 0.56 kgf) (LMM, $p < 0.001$).

When observed in the 800-l tanks and during fishing, all conical hoop nets had their apex ~830 mm from the bottom and with taut meshes. By comparison, the inverted hoop nets had many meshes on the bottom, but with some and especially in the thicker-twined (stiffer) multi-monofilament PA, displaced upwards (to ~200 mm) either side of the line used to secure the bait bags (Fig. 1c).

3.1. Fishing conditions

Between four and ten replicates of each hoop net were deployed in the Corindi River and Wallis Lake up to nine times diurnally (for soaks

of 2.3–5.1 and 3.0–4.0 h, respectively) and nocturnally (for between 15.3–18.5 and 11.7–17.3 h, respectively). While the fished depths at each location remained comparable (means \pm SD of 1.5 ± 0.4 and 1.9 ± 0.6 m), water temperatures and salinities were greater in the Corindi River (28.2 ± 2.0 °C and 35.3 ± 0.7) than Wallis Lake (23.7 ± 1.0 °C and 33.1 ± 1.4).

3.2. Hoop-net damage and marine debris

Consistently more damage (by up to 2 \times) occurred among hoop nets when targeting *S. serrata* than *P. pelagicus* and was clearly biased towards the multifilament configurations, with a maximum of 172 broken/missing bars and 7.3 m of twine lost as debris from one conventional multifilament hoop net during a nocturnal deployment for *S. serrata* (Table 1). Subsequently, the chosen GLMMs and LMMs revealed a significant main effect of hoop net for both net-damage response variables ($p < 0.05$; Table 2, Fig. 2). When targeting *S. serrata*, compared to the conventional, conical multifilament hoop net (which averaged 8.4 ± 1.1 broken/missing bars and 130.6 ± 23.1 mm of missing twine 3-h soak⁻¹), both multi-monofilament hoop nets had up to 78% less damage (FDR, $p < 0.05$, Fig. 2a and b). Similarly, while damage among the multifilament hoop nets was much lower when targeting *P. pelagicus* (but significantly less in the conical than inverted configuration; 1.1 ± 0.13 vs 2.4 ± 0.3 broken/missing bars and 5.3 ± 1.2 vs 27.4 ± 7.3 mm of twine missing 3-h soak⁻¹), both multi-monofilament designs had significantly fewer broken/missing bars and twine loss (by >95%; FDR, $p < 0.05$; Fig. 2b and d).

Irrespective of their twine or fishing configuration, hoop nets targeting *S. serrata* were more frequently damaged during warmer water temperatures and lower salinities, while standardised twine loss was greater during nocturnal (e.g. 92.5 ± 11.1 mm 3-h soak⁻¹) than diurnal (65.6 ± 15.4 mm 3-h soak⁻¹) deployments (LMM, $p < 0.05$; Table 2). Similarly, significantly more broken/missing bars and twine loss occurred in all hoop nets targeting *P. pelagicus* at night (1.4 ± 0.2 and 16.4 ± 3.6 mm 3-h soak⁻¹) than during the day (0.7 ± 0.1 and 1.3 ± 0.1 mm 3-h soak⁻¹) (GLMM and LMM, $p < 0.001$; Table 2).

Table 1
Summary of catches and damage to hoop nets deployed (i) nine times diurnally (over 2.3–5.1 h) and nocturnally (15.3–18.5 h) in the Corindi River, NSW to target giant mud crabs, *Scylla serrata* and (ii) eight times diurnally (3.0–4.0 h) and nine times nocturnally (11.7–17.3 h) in Wallis Lake, NSW to target blue swimmer crabs, *Portunus pelagicus*. CM, conventional multifilament, IM, inverted multifilament, CMM, conventional multi-monofilament, and IMM, inverted multi-monofilament.

	<i>S. serrata</i>				<i>P. pelagicus</i>			
	CM	IM	CMM	IMM	CM	IM	CMM	IMM
Total number of deployments	90	90	89	91	142	140	141	140
<i>Portunid</i>								
Total no. caught	92	58	115	94	98	71	111	101
% of total no. undersized	5.4	10.3	11.3	10.6	11.2	23.9	12.6	22.8
No. of recaptured individuals	21	8	22	10	2	1	4	7
No. of recaptures	27	9	27	13	2	2	4	7
Sex ratio (M:F) of total caught	1.7:1	2.0:1	1.5:1	1.2:1	4.4:1	7.0:1	4.8:1	6.8:1
No. of ovigerous females with egg damage	0/0	0/0	0/0	0/0	0/0	2/2	2/2	2/2
Moult stages of total caught								
Post-moult	12	1	10	13	7	2	13	10
Early inter-moult	41	25	51	41	150	88	136	132
Late inter-moult	39	31	52	40	48	78	90	75
% of total caught with new exoskeleton damage	21.7	25.9	20.4	24.0	9.2	15.3	8.1	10.9
Mean (SD) no. of damaged limbs	2.2 (1.7)	1.2 (0.4)	1.3 (0.6)	1.5 (1.4)	1.7 (0.8)	1.8 (0.5)	1.3 (0.5)	0.8 (0.3)
Mean time (SD) to remove from net (s)	97.0 (82.6)	62.0 (62.2)	118.0 (100.1)	103.1 (98.2)	58.8 (45.7)	45.6 (43.7)	50.8 (48.7)	43.4 (40.9)
Net damage								
% of total damaged	83.3	80.0	83.1	80.2	55.6	67.1	31.9	41.4
% of total replaced	56.7	48.9	33.7	37.3	14.1	23.6	<0.0	<0.0
Bycatch no.								
Yellowfin bream, <i>Acanthopagrus australis</i>	3	4	3	1	0	0	0	0
Black spotted cod, <i>Epinephelus malabaricus</i>	1	0	0	4	0	0	0	0
Trumpeter, <i>Pelates quadrilineatus</i>	0	0	0	0	3	2	0	0
Leatherjacket, <i>Monacanthus chinensis</i>	0	0	0	0	0	0	1	0
Shovelnose ray, <i>Aptychotrema rostrata</i>	0	0	0	0	0	0	0	1

Table 2

Summary of factors tested in parsimonious mixed-effects models (generalized linear mixed models for all variables except CL and twine missing which were analysed in linear mixed models) applied to data from conventional and inverted multifilament and multi-monofilament hoop nets targeting (a) giant mud crabs, *Scylla serrata* and (b) blue swimmer crabs, *Portunus pelagicus* during both the day and night. The significance of various response variables is represented by: – $p > 0.05$, * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$.

	Hoop net (H)	Diel deployment (D)	H × D	Depth	Water temperature	Salinity
Experiment 1						
<i>Scylla serrata</i>						
No. of total	–	***	***	–	–	–
No. of legal-sized	–	***	*	–	–	–
No. of undersized	–	***	–	–	–	–
CL	**	–	–	–	*	–
Exoskeleton damage	–	–	–	–	–	–
No. of broken/missing mesh bars	**	–	–	–	***	**
Total length of twine missing	*	**	–	–	**	*
Experiment 2						
<i>Portunus pelagicus</i>						
No. of total	*	*	–	–	–	–
No. of legal-sized	**	**	–	–	–	–
No. of undersized	–	–	–	NA	NA	NA
CL	**	*	–	–	–	–
Exoskeleton damage	–	–	–	–	–	–
No. of broken/missing mesh bars	***	***	–	–	–	–
Total length of twine missing	***	***	–	–	–	–

3.3. Catches

In total, 360 and 381 *S. serrata* and *P. pelagicus* were caught (with a maximum of 5 of each species in a single hoop net), including 76 and 15 recaptures, respectively (Table 1). Both species mostly comprised legal-sized individuals (>90 and 82%, respectively), and with biases towards males (especially among *P. pelagicus*) and intermoult (Table 1). All individuals were quickly removed from the

hoop nets and although ~22 and 11% of *S. serrata* and *P. pelagicus* were damaged (typically limited to <2 missing limbs), only one *S. serrata* died (Table 1). Six *P. pelagicus* were ovigerous, and three had obvious damage to their eggs (Table 1). The non-portunid catches comprised only 23 individuals, and mostly yellowfin bream, *Acanthopagrus australis* and trumpeter, *Pelates quadrilineatus* (Table 1). Only four fish were dead (all *A. australis* when targeting *S. serrata*).

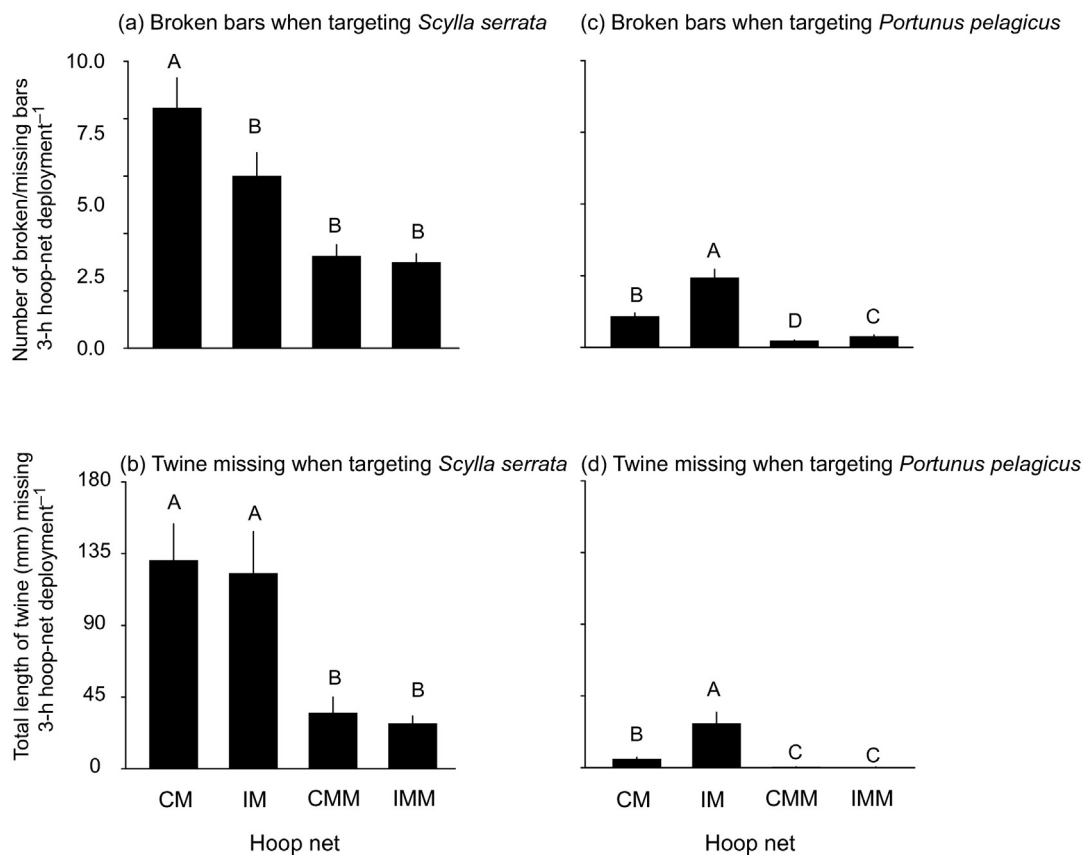


Fig. 2. Differences among the conical and inverted multifilament (CM and IM) and multi-monofilament (CMM and IMM) hoop nets in the mean (+SE) number of broken/missing bars and missing total length of twine 3-h soak⁻¹ for (a and b) *Scylla serrata* and (c and d) *Portunus pelagicus*. Dissimilar letters above histogram represent significant differences in false-discovery-rate pairwise comparisons ($p < 0.05$).

The chosen GLMMs describing the total, and legal- and undersized numbers of both portunids were reduced to the fixed effects of either hoop net or diel deployment, or their interaction (Table 2). But, all significant hoop-net related differences were limited to total and legal-sized catches, which followed the same intra-specific patterns (and so only legal-sized catches were graphed) (GLMM, $p < 0.05$; Table 2, Fig. 3).

For *S. serrata*, the hoop net \times diel interaction was significant with FDRs revealing no differences in either standardised (for soak time) total or legal-sized catches among diurnally fished hoop nets ($p > 0.05$; Fig. 3a), but significantly fewer individuals (by up to 70%) in the inverted multifilament hoop nets than all other treatments during nocturnal deployments ($p < 0.05$, Fig. 3b). Further, while there were slightly fewer individuals in the inverted than conical multi-monofilament hoop nets (FDR, $p < 0.05$), both caught similar numbers of legal-sized *S. serrata* as the conical multifilament hoop net (FDR, $p > 0.05$, Fig. 3b). For legal-sized *P. pelagicus*, there was no significant hoop net \times diel interaction, but still a similar trend as above of fewer catches (across all deployments) retained in the inverted multifilament hoop net than the others (FDR, $p < 0.05$)—although the pairwise difference with the inverted multi-monofilament hoop net was not significant (FDR, $p > 0.05$; Fig. 3c). Irrespective of hoop net, catches of undersized *S. serrata* and total and legal-sized *P. pelagicus* 3-h soak⁻¹ were significantly greater during diurnal (by up to 10 and 1.5 times, respectively) than nocturnal deployments (GLMM, $p < 0.05$, Table 2, Fig. 3a and b).

Variation among the CLs of both *S. serrata* and *P. pelagicus* was also significantly affected by hoop nets, and with an identical trend of larger mean sizes in the conical hoop nets, and especially the multifilament design (101.8 ± 1.4 and 69.5 ± 1.3 mm CL, respectively) than either the inverted multifilament (97.0 ± 1.6 and 66.3 ± 1.3 mm CL) or multi-monofilament (97.8 ± 1.3 and 66.7 ± 1.3 mm CL) hoop nets (LMM, FDR, $p < 0.05$, Table 2, Fig. 4). For *S. serrata*, larger individuals were caught with increasing water temperature, while significantly larger *P. pelagicus* were caught during the day (68.24 ± 0.77 mm CL) than at night (65.10 ± 0.40 mm CL) (LMM, $p < 0.05$; Table 2). None of the fixed effects, including CL, explained the limited exoskeleton damage to either species (GLMM, $p > 0.05$; Table 2).

4. Discussion

This study showed that, irrespective of their configuration, conventional multifilament PA hoop nets used in NSW consistently produce marine debris—the extent of which substantially varies according to several biological (i.e. the species targeted) and environmental (i.e. water temperature and salinity and diel deployment) factors. By assessing hoop nets made from an alternative twine, we have also shown that a simple technical factor can supersede all other influences and dramatically reduce debris, while still maintaining targeted catches. These results can be discussed with respect to the inherent characteristics of the assessed twines and the catchability of portunids, and then used to recommend management options.

However, prior to considering any underlying mechanisms and/or resolution strategies, quantitative estimates of total hoop-net debris are warranted to place this issue in perspective. There are few data describing the spatio-temporal use of hoop nets throughout NSW, but the total number of recreational fishers is between 0.8 and 1 million (Henry and Lyle, 2003; West et al., 2015). All fishers are legally permitted to deploy two baited pots (typically collapsible round netted designs; Butcher et al., 2012; Leland et al., 2013) and four baited hoop nets—regulations that imply the potential for considerable effort.

During a recent phone survey in NSW, West et al. (2015) and L. West (pers. comm.) estimated the total estuarine recreational trap effort at ~1.2 million trap-hours (separated into ~0.21, 0.54 and 0.45 million trap-hours targeting *P. pelagicus*, *S. serrata*, and both species combined, respectively) in the 12 months prior to May 2014. Considering the mean twine losses estimated for conventional conical multifilament hoop nets, if: (i) this gear comprised ~66% of the total trap effort (i.e. 4/6

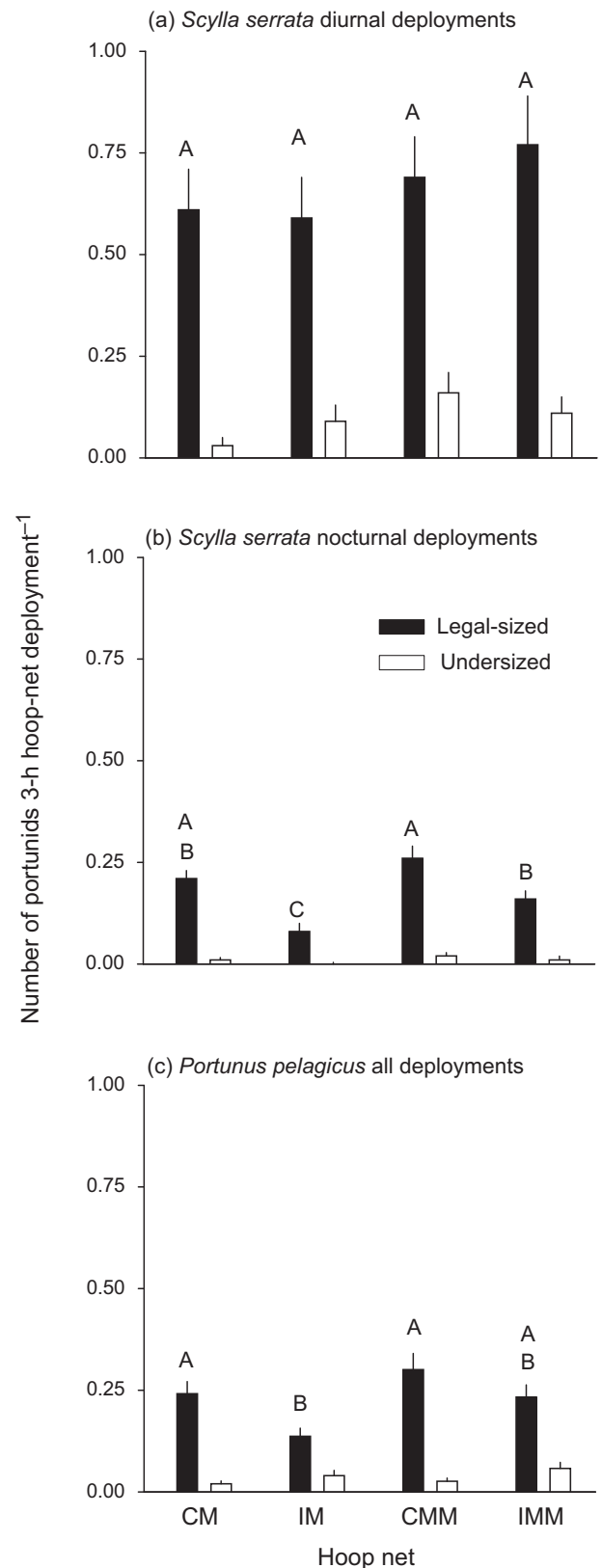


Fig. 3. Differences among the conical and inverted multifilament (CM and IM) and multi-monofilament (CMM and IMM) hoop nets in the mean number (+SE) 3-h soak⁻¹ of (a) diurnally and (b) nocturnally caught *Scylla serrata*, and (c) all *Portunus pelagicus*. Dissimilar letters above histogram represent significant differences in false-discovery-rate pairwise comparisons ($p < 0.05$).

baited traps allowed per fisher); and (ii) the partitioned effort remained

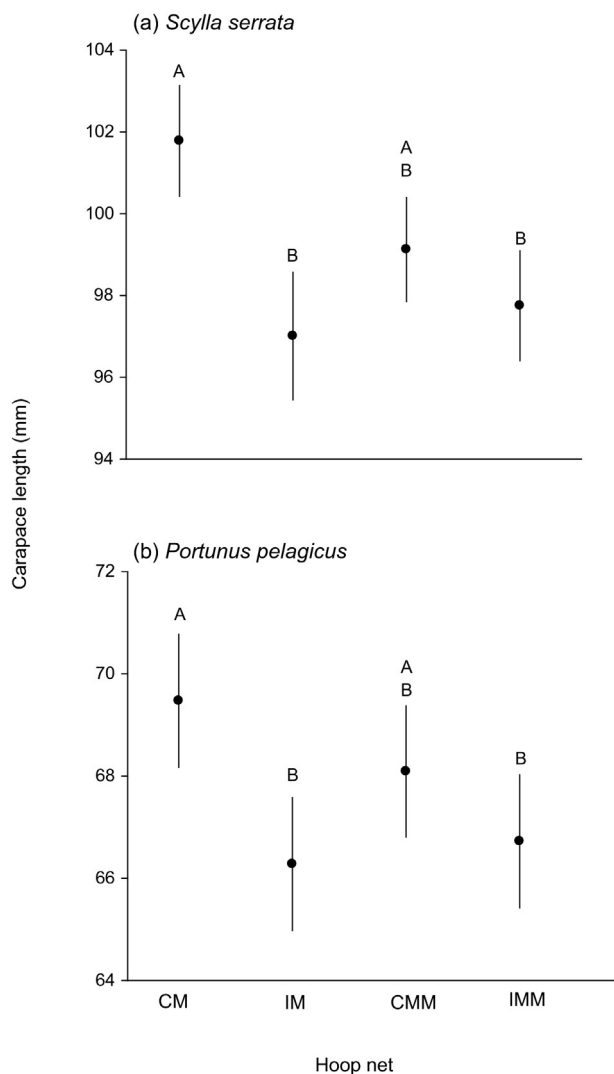


Fig. 4. Differences among the conventional and inverted multifilament (CM and IM) and multi-monofilament (CMM and IMM) hoop nets in the mean carapace length (\pm SE) of all (a) *Scylla serrata* and (b) *Portunus pelagicus*. Dissimilar letters above the error bars represent significant differences in false-discovery-rate pairwise comparisons ($p < 0.05$).

consistent where fishers indicated both species were combined, then twine loss could be ~25,000 and 400 m when targeting *S. serrata* and *P. pelagicus*, respectively. Further, the existing recommendation of inverting hoop nets would dramatically increase twine loss when targeting *P. pelagicus* from ~400 to >2000 m (and with a concomitantly lower catch efficiency).

Obviously, such quantitative estimates are subject to broad assumptions, including inter-annual effort variability and associated variances, and most importantly the unknown division of pot and hoop-net use. Typically, hoop nets are more commonly used among fishers targeting *P. pelagicus* than *S. serrata*, but even if conventional hoop nets were only deployed for 5% of the total estimated trap-hours targeting *S. serrata*, the twine loss would still be almost 2000 m per annum. Another important consideration is that we assessed the strongest available conventional multifilament twine. Many fishers use lighter twine, and with a clear negative correlation with breakage (Broadhurst et al., 2015). If lost as single strands, all of these multifilament twines would unravel into their component fibres, and present as much greater linear micro debris (Rocjman et al., 2015). Further, we have not considered the complete loss of hoop nets (~54 m of twine per net; which can occur based on anecdotal sightings of the ring bases in estuaries).

Notwithstanding considerable uncertainty in the total estimated debris caused by hoop nets, it is clear that simply substituting multifilament with multi-monofilament in either conical or inverted configurations would reduce linear twine loss by up to 78 and 95% when targeting *S. serrata* and *P. pelagicus*. It is also apparent that, unlike inverting multifilament hoop nets, there would be no significant negative impacts on targeted catches of either species associated with using the tested configurations of multi-monofilament hoop nets.

The observed variation among twine loss and catches between the treatment hoop nets might be explained by the different material properties and density-dependant, inter-specific behaviour along with some confounding interactive effects of fishing height. At a broad level, the multi-monofilament was 1.7 \times stronger than the multifilament, which simply meant that it more securely entangled portunids as they attempted access to the bait (and with less bar breakage), especially during low catches. For example, during diurnal deployments for *S. serrata*, neither material nor configuration affected catches, presumably because there were large numbers of aggressive individuals that were rapidly entangled among multiple meshes, irrespective of the material. But, during the relatively lower standardised catches of *S. serrata* at night and *P. pelagicus* irrespective of diel period, both inverted hoop nets were less efficient than their conical configurations at retaining legal-sized portunids (also evidenced by the smaller mean CLs), and especially the inverted multifilament hoop net which had the lowest catches of all treatments.

While both twines had densities >1 (and were negatively buoyant), because the multi-monofilament was quite stiff, many meshes in the inverted hoop nets were observed to be displaced upwards, which probably facilitated entangling portunids (although perhaps not to the same extent as a conical design). By comparison, inverted hoop nets made from the softer multifilament tended to have more meshes closer to the substrate and were somewhat convoluted, which may have allowed portunids to walk across with less chance of entanglement. The poorer ability of the inverted multifilament hoop net to retain individuals might also explain why these nets incurred greater damage when targeting the smaller-bodied *P. pelagicus* (as these escaped and were replaced by their conspecifics).

The low non-portunid catches by any hoop net precluded assessing the utility of inversion for mitigating bycatch interactions, but intuitively because of their lower fishing height (and based on a positive correlation with non-portunid catches observed for other entangling gears; Gray et al., 2005), such nets might catch fewer *C. mydas*. Depending on inter-specific differences in visual responses, it could also be feasible to increase the visibilities of conical and/or inverted hoop nets (and any subsequent *C. mydas* interactions) using similar concepts as those described for gill nets (e.g. via UV illumination; Wang et al., 2013).

Irrespective of rare bycatch mitigation, the results here provide clear direction for managing perhaps the more high-profile issue of debris from hoop nets. One obvious option is to prohibit the gear—especially considering there are other equally efficient alternatives with few environmental impacts (e.g. lift nets; Broadhurst et al., 2016). But, there remains resistance to remove what is considered an inexpensive, easily used and effective fishing method. In the absence of complete restrictions, associated marine debris could be minimised (and target catches maintained) simply by mandating multi-monofilament, and/or considering the key biological and environmental factors identified here.

In particular, irrespective of material, short diurnal rather than long nocturnal sets would dramatically reduce twine loss (e.g. by 29 and 50% when targeting *S. serrata* and *P. pelagicus*, respectively). Butcher et al. (2012) and Leland et al. (2013) hypothesised that maximum hoop-net efficiency is achieved within <3–6 h. Deploying nets for longer periods overnight precludes additional portunids being caught, but clearly results in ongoing twine loss (as individuals continue to attempt access to the bait). Prohibiting nocturnal deployments would be an effective option for limiting debris.

In addition to diel effects on hoop-net damage were positive and negative influences of water temperature and salinity when targeting *S. serrata*; a result that may simply reflect greater portunid activity within their desired ranges (e.g. Meynecke et al., 2012). While neither of these parameters might support fine-scale spatio-temporal restrictions, they could be used to direct broader regulations. For example, nocturnal sets might be limited during peak warmer months, particularly in northern estuaries (which are dominated by *S. serrata*) to minimise hoop-net damage. Similar-themed temporal regulation of commercial gill nets (targeting *Platycephalus fuscus*) has been regionally imposed to promote discard survival (Broadhurst et al., 2009), although any associated diel effects on unwanted bycatch (including *C. mydas*) would warrant consideration.

Irrespective of the approach taken, and in addition to unwanted bycatches, there should be a strong focus on reducing marine debris, and although twine loss from hoop nets is probably only a small component of regional derelict fishing gear (Chiappone et al., 2005), complete sections of missing mesh could cause entanglements with considerable negative consequences. Eliminating marine debris and unwanted species interactions by promoting alternative yet simple, environmentally benign gears would seem a coherent policy and one that is likely to gain momentum. By proactively seeking alternatives such as those assessed here, recreational fishers could be given a greater choice of acceptable solutions.

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