Reducing bycatch using modifications to sweeps and lines anterior to the trawl mouth - collaboration with the Technical University of Denmark

FINAL REPORT

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Table of Contents

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Executive Summary

Prawn trawling is among the world's least selective fishing methods and there has been a great deal of work done over the past few decades to develop modifications that reduce unwanted bycatches. Much of this work has focussed on modifications at, or near, the codend (at the aft section) of trawls, but more recent efforts have examined ways to stop fish entering the trawl at all—via modifications to their anterior components (or forward section).

New South Wales (NSW) Department of Primary Industries (DPI) Fisheries Conservation Technology Unit (FCTU) has led such work with prawn trawls in Australia. Another group based in Denmark (the Danish Technical University's team in Hirtshals – DTU Aqua) has grown to be among the European leaders with similar work directed at *Nephrops* and fish trawls and is a major centre for work being done to underpin the European 'landings obligation' (often termed the 'discard ban'). The current project took advantage of a travel grant for a PhD student at DTU Aqua to: (i) establish a link and exchange of ideas between the Australian and the Danish teams; whilst (ii) exploring ways of refining anterior-trawl modifications to reduce bycatch in our prawn fisheries.

The research involved two experiments in Lake Wooloweyah (part of the Clarence River prawn-trawl fishery). The first experiment examined how a modification based on the theory behind the FLEXSELEECT design involving counter herding (developed by the DTU Aqua group) performed in combination with the SAFE modification developed by the NSW DPI FCTU during the FRDC project 2011/010 "Reducing the environmental impacts and improving the profitability of prawn trawling through a structured framework of anterior gear modifications". The FLEXSELECT concept uses a series of lines extending from the otter boards to the trawl in a cross configuration to herd fish outwards, instead of inwards as occurs with conventional sweeps in fish trawls—effectively making these lines 'reverse sweeps'. In the second experiment, we examined the utility of simply lowering headline height at the otter boards which, if it reduces bycatch as hypothesised in the earlier FRDC project, could provide an adaptive and rapid tool for fishers to use *in situ*.

The results confirmed the utility of the SAFE design as developed previously, but its combination with the FLEXSELECT concept did not perform any better in reducing bycatches. However, the lowering of headline height in the second experiment dramatically reduced the bycatches of small fish without any effects on prawn catches. This result

showed that a very simple modification could be used by fishers to adapt their practices at key locations and times of large fish abundances—which may be useful, for example, in avoiding the triggering of bycatch caps that lead to fishing closures in some of NSW's estuarine and oceanic prawn-trawl fisheries.

The collaboration with DTU Aqua was a significant success in establishing a relationship with one of the most important gear technology groups in the world—at a time when Australia's jurisdictions are (unfortunately) reducing priorities in this area. This places Australia in a good position to learn of any new European efforts in bycatch reduction as their 'landing obligation' is implemented.

The project led to a very useful cross-fertilisation of gear concepts and analytical treatments while allowing us to continue to test anterior modifications to prawn trawls. We therefore recommend ongoing communications with DTU Aqua via the PI on this project (IC Independent Consulting) and/or other gear technologists in Australia (including Smart Fishing Consulting) to develop collaborative opportunities. Notwithstanding the success of this collaboration, we also concluded that like previous work done with BRDs, anterior trawl modifications should ideally be developed on a fishery-by-fishery basis. For this reason, it is important that Australia maintains its local expertise to develop bycatch reduction technologies.

Keywords

Bycatch Reduction, Prawn Trawl, Anterior trawl modifications

Introduction

Prawn trawling is among the world's least selective fishing methods, catching and discarding large quantities of unwanted non-targeted finfish and other organisms (collectively called 'bycatch'). The mortality of bycatch is considered wasteful and attracts significant attention and/or controversy from a host of stakeholders including other commercial and recreational fishers, environmental groups, eco-labelling organisations and the general public. Despite decades developing various bycatch reduction technologies (involving trawl modifications such as various grids, square mesh panels, etc.) significant bycatches still occur in many fisheries, indicating that there remains some way to go in developing better bycatch reduction technologies and practices and/or getting those that are available implemented as mainstream fishing gears.

NSW DPI's Fisheries Conservation Technology Unit (FCTU) has been among the leaders in Australia in developing technologies for reducing bycatch and/or its mortality among prawn-trawl fisheries. But another group based in Denmark (the Danish Technical University's team in Hirtshals – DTU Aqua) has grown to be among the European leaders in developing solutions for other types of trawl fisheries (e.g. Nephrops) and is a major centre for work being done to underpin Europe's implementation of its 'landings obligation' (often termed the 'discard ban'). This latter group has significant infrastructure and personnel working in bycatch reduction and especially in developing modifications anterior to the mouth of Nephrops trawls—related in concept to research that was the focus of a recent four-year FRDC project (2011/010 - Reducing the environmental impacts and improving the profitability of prawn trawling through a structured framework of anterior gear modifications) in Australia. A PhD student at DTU received funding to travel to Australia to establish a link and exchange of ideas between the Australian and the Danish teams, whilst exploring ways of refining anterior-trawl modifications to reduce bycatch in our prawn fisheries.

Objectives

1. Establish a collaboration with the Technical University of Denmark's fishing gear technology centre via a shared piece of research done in an Australian fishery.
2. Conduct two experiments to develop novel modifications anterior to the trawl mouth that will reduce the bycatch of unwanted finfish.
3. Disseminate the results to the prawn-trawl fisheries of Australia and produce appropriate scientific papers and the final report.

Methods

General

This project involved two experiments focused on refining modifications anterior to the trawl mouth that would reduce the bycatch and subsequent discarding of fish from prawn trawls. The work was done in Lake Wooloweyah (part of the Clarence River prawn-trawl fishery)—which has proven itself as an ideal testing ground for such modifications—using two chartered, local commercial trawlers.

The project took advantage of the hosting of the PhD student from DTU Aqua (Ms Valentina Melli) at Southern Cross University and NSW Department of Primary Industry's (DPI's) FCTU facilities at Coffs Harbour. Ms Melli's visit was sponsored by Europe's Idella Foundation and the Technical University of Denmark. Her thesis includes examining modifications to sweeps that involve the FLEXSELECT design for Nephrops trawls—a series of lines extending from the boards to the net in a cross configuration. This takes advantage of the fish-herding effect of such lines to scare fish away from it, instead of attracting them into the path of the net as occurs with conventional sweeps in fish trawl gear—effectively making these new lines 'reverse sweeps'.

In addition to testing a variation of the FLEXSELECT design involving chains on the seabed anterior to Clarence River trawls, we applied a similar concept to the existing simple anterior fish excluder (SAFE). The SAFE was one of the more promising modifications developed during the former FRDC project (2011-010 - Reducing the environmental impacts and improving the profitability of prawn trawling through a structured framework of anterior gear modifications), and various recommendations were made for its ongoing refinement, including those encapsulated in the subsequent FLEXSELECT design tested in Europe. We also examined the utility of simply varying headline height at the otter boards—which was also recommended for testing in the earlier FRDC project.

This project began with inception meetings among all scientists involved, including Ms Melli's PhD supervisor and leader of the Danish centre (Dr Ludvig Ahm Krag). At these meetings, we finalised the proposed modifications to be initially tested and the experimental designs for the field work.

Details of the two experiments and their results are provided in the two draft manuscripts that arose from the project which are appended to this report as Appendices 1 and 2. A summary of the experiments is provided below (details regarding the references cited can be found in the appended papers).

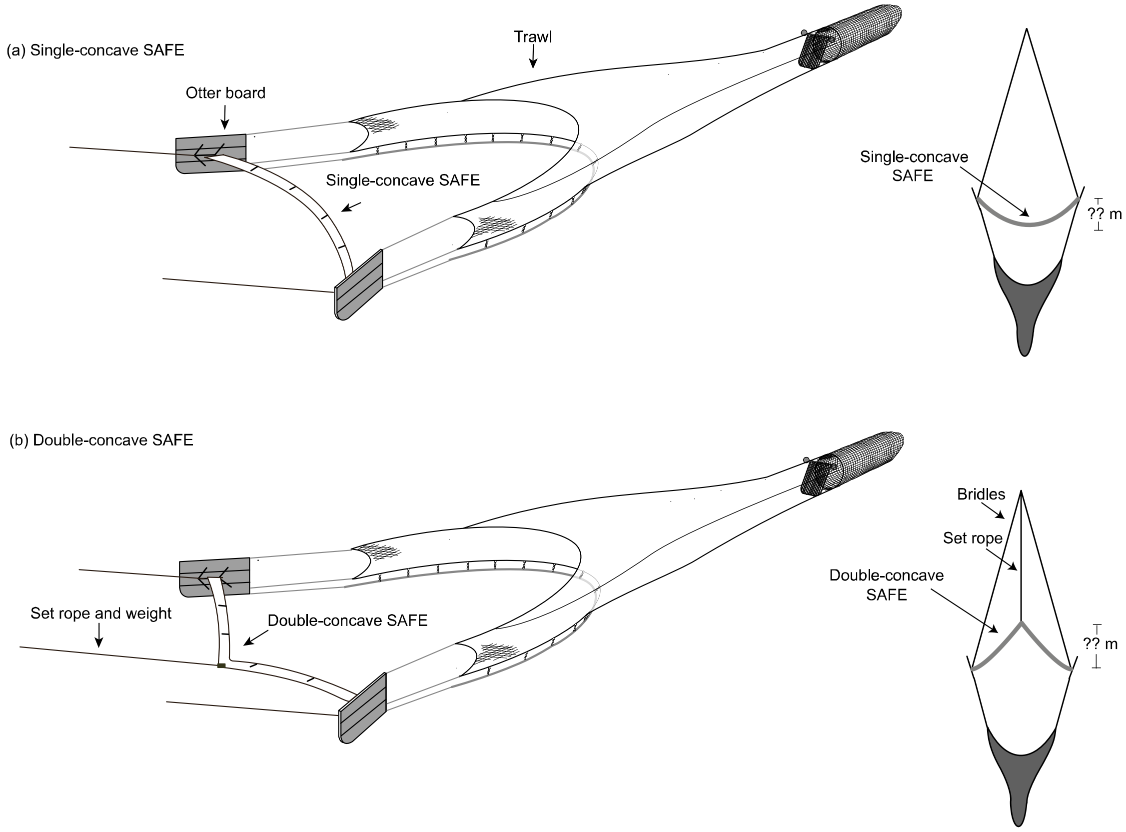
Gear and experimental designs

We used two double-rigged trawlers (10 m and 89 kw) (one for each experiment) fishing across sandy and muddy substrata in in Lake Woolooweyah in ~2 m of water. Each trawl comprised nominal 41-mm mesh (stretched mesh openings—SMOs) throughout, 1N3B body tapers, rolled-rope ground gear with lead weights, an extension section (100 T × 30 N of 40 mm mesh; with 28-mm bar spaced Nordmøre-grids installed) and codend (120 × 75 B; made from 27-mm mesh hung on the bar). During fishing, Notus monitoring sensors were attached at each wing end to measure the spread (providing 20 replicates per haul) while a

Lowrance global positioning system (GPS) was used to record the distance trawled and speed across the ground (SOG).

For experiment 1, two identical SAFEs were constructed (Fig. 1). One SAFE was rigged so that it could be pulled forward approximately 1.5 m by a 4-mm Ø polyethylene rope (with a 2.4 kg weight clipped at the centre) back to the towing point to form two (double) concave shapes, while the other was left as a single-concave configuration. The trawls with either version of the SAFE were tested against a control trawl (i.e. no SAFE) in alternate, simultaneously paired deployments. Irrespective of their treatment, the two trawls were swapped from side-to-side each day after the first three deployments.

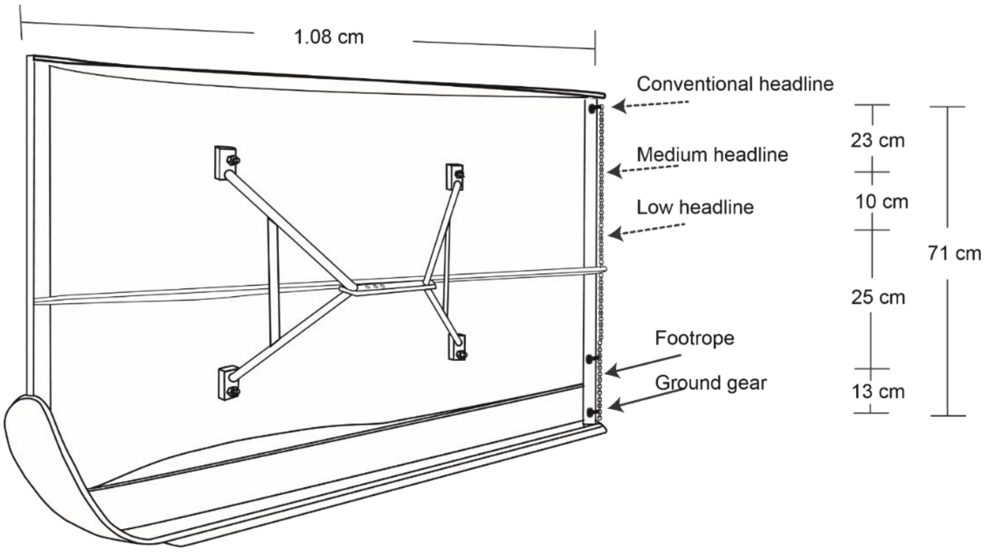
Fig. 1 - Three and two-dimensional diagrams of the (a) single-concave and (b) double-concave SAFEs attached to the penaeid trawl.



For experiment 2, we attached a 0.73-m length of 8-mm chain along the trailing edge of each board to provide multiple attachment points (i.e. at any of the chains' links) for the headline (Fig. 2). The headline attachments included: (1) the conventional attachment at 0.71 cm above the ground chain; (2) a medium attachment at 48 cm (or 67%) above the ground chain; and (3) a low attachment at 38 cm (or 54%) above the ground chain, slightly above the midpoint of the otter board (to maintain stability). Snap clips that fit through the attachment points were shackled to 2.93-m sweeps and then to the ground chains, foot ropes and headlines of two identical trawls. The headline heights were randomly assigned so that we compared the conventional 71 cm against each of the medium (48 cm) and low

(38 cm) headline heights, and the latter two against each other (i.e. all three possible combination of configurations) in alternate, simultaneously paired 30-min deployments and with the paired Notus trawl sensors attached at the wing ends. The two trawls were swapped from side-to-side at the beginning and halfway through each trawling day.

Fig. 2 – Otter board and sweep attachment points



Data analyses

For each deployment, technical data were collected including the total distance towed, speed over the ground (SOG), and the average wing-end spreads. Biological data collected included the total weights of School Prawns and bycatch, the numbers of each bycatch species, and total lengths (TL in mm to the nearest 0.5 cm) of the teleosts. For abundant teleost species, subsampling was sometimes necessary and the sampling factor was obtained dividing the number of individual length-measured by the total. Random samples of School Prawns were placed into plastic bags and transferred to the laboratory, where 100 individuals were measured (carapace length – CL to the nearest 1 mm) and weighed. The length distributions, implemented by the use of a length-weight relationship, were used to estimate the total number of School Prawns caught.

Data were analysed in linear mixed models (LMM). Catches were considered both as (1) absolute and (2) standardised to ha^{-1} trawled using the swept area of the trawl (calculated by average wing-end spread × distance trawled). In both cases, data were log-transformed so that differences between gears were modelled to act multiplicatively. The significance of gear configuration was determined using a Wald *F*-test and any significant differences were subsequently explored using the Benjamini-Hochberg-Yekutieli procedure to control the false discovery rate (FDR).

For those species caught in sufficient quantities, we conducted a length-dependant catch-comparison analysis (SELNET; Herrmann et al., 2012), following the methodology of Krag et al. (2015) and including recent model improvements developed by Herrmann et al. (2017).

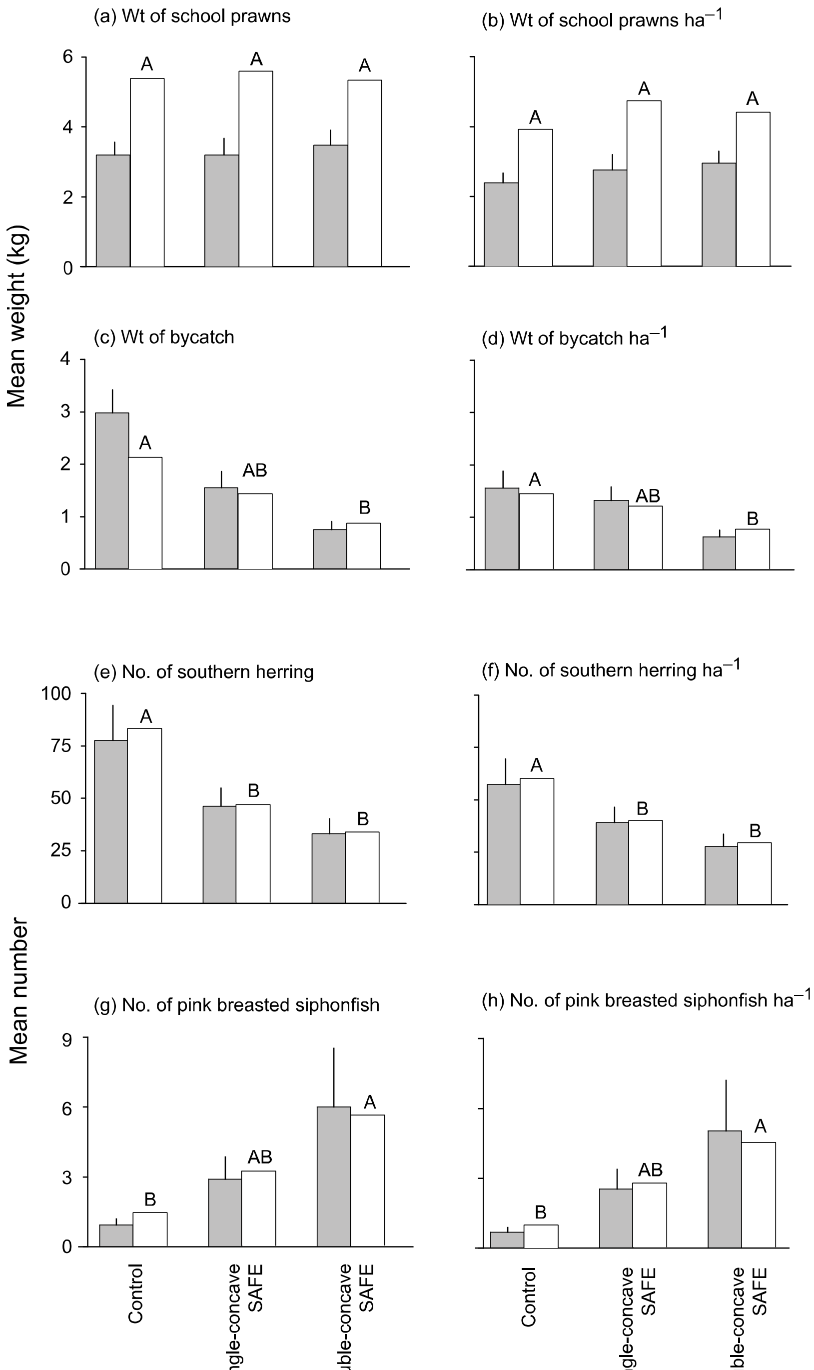
Results

Experiment 1

Among the species caught, School Prawns were dominant (92% of catches by number), while seven species (of 18 in total) comprised 99% of the total fish bycatch. These data formed the basis of biological analyses. Linear mixed models did not detect any significant differences between anterior configurations for either the absolute or standardized (i.e. ha^{-1} trawled) weights or numbers of School Prawns (Fig. 3a and b). A significant effect of anterior configuration was detected for both the absolute and standardised numbers and weights of bycatch (Fig. 3c and d), of Southern Herring, *Herklotsichthys castelnaui* and Pink Breasted Siphonfish, *Siphamia roseigaster* (Fig. 3 e–h).

False discovery-rate-pairwise comparisons revealed that trawls rigged with the single- and double-concave SAFE similarly and significantly (p<0.05) reduced the absolute and standardised numbers of Southern Herring by up to 50 and 59%, respectively (Fig. 3e and g). Because Southern Herring was one of the most abundant species, these reductions manifested as comparable effects on the weights and numbers of absolute and standardised total bycatch (by up to 52%; Fig. 3c and d). Conversely, the least abundant analysed species, Pink Breasted Siphonfish, was retained in significantly greater absolute (by up to 3.8×) and standardised numbers (4.0×) in trawls with either SAFEs than in the control (Fig. 3g and h).

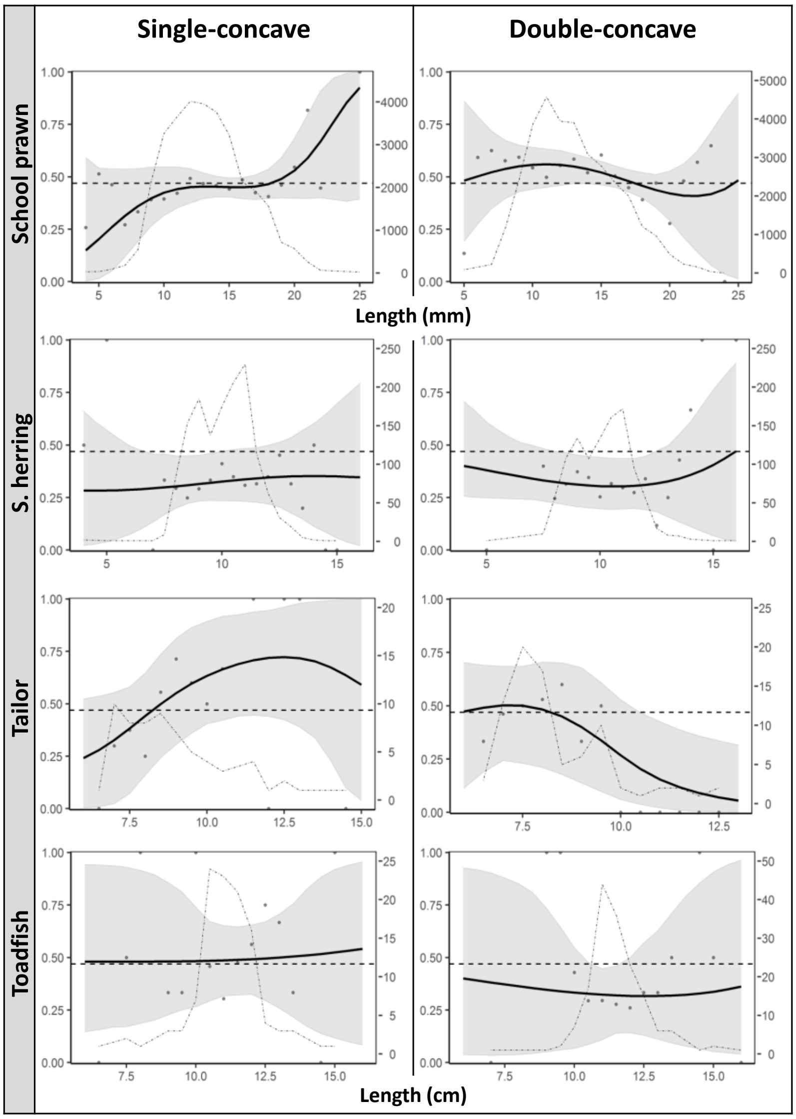
Fig 3. - Differences in raw (+SE) and predicted mean catches between trawls without (control) the simple anterior fish excluder (SAFE) and those with a single- and double-concave SAFE for the (a) absolute and (b) ha^{-1} trawled weights of School Prawns, *Metapenaeus macleayi*, (c) absolute and (d) ha^{-1} trawled weights of bycatch and the numbers of (e) absolute and (f) ha^{-1} trawled Southern Herring, *Herklotsichthys castelnaui* and (g) absolute and (i) ha^{-1} trawled Pink Breasted Siphonfish, *Siphamia roseigaster*. Dissimilar letters above the predicted means indicate significant differences detected in false-discovery-rate pairwise comparisons (p < 0.05).



The SAFEs did not significantly affect catches of the targeted School Prawns for any of the length classes represented (Fig. 4). Compared to the conventional trawl, those with either SAFE caught significantly less Southern Herring of 7-9.5 and 8-12.5 cm with the single- and double-concave SAFE, respectively. Tailor and Toadfish were affected by the double-concave SAFE but only for few length classes (10.5-12.5 and 11-11.5 cm for Tailor and Toadfish, respectively. No effect was detected on the catch of Forktail Catfish in either experiment.

Fig.4 - Catch comparison curves of trawls with the single- and double-concave SAFEs respect to the control trawl of the target School Prawns, *Metapenaeus macleayi*, and three of the fish species

analysed. The curves (solid lines) represent the modeled catch efficiency fitted to the experimental points (dots). The dashed horizontal lines indicate the baseline for no difference in catch efficiency between the trawls. The shaded areas represent the 95% confidence intervals while the dot-dashed lines depict the underlying size frequencies.



Experiment 2

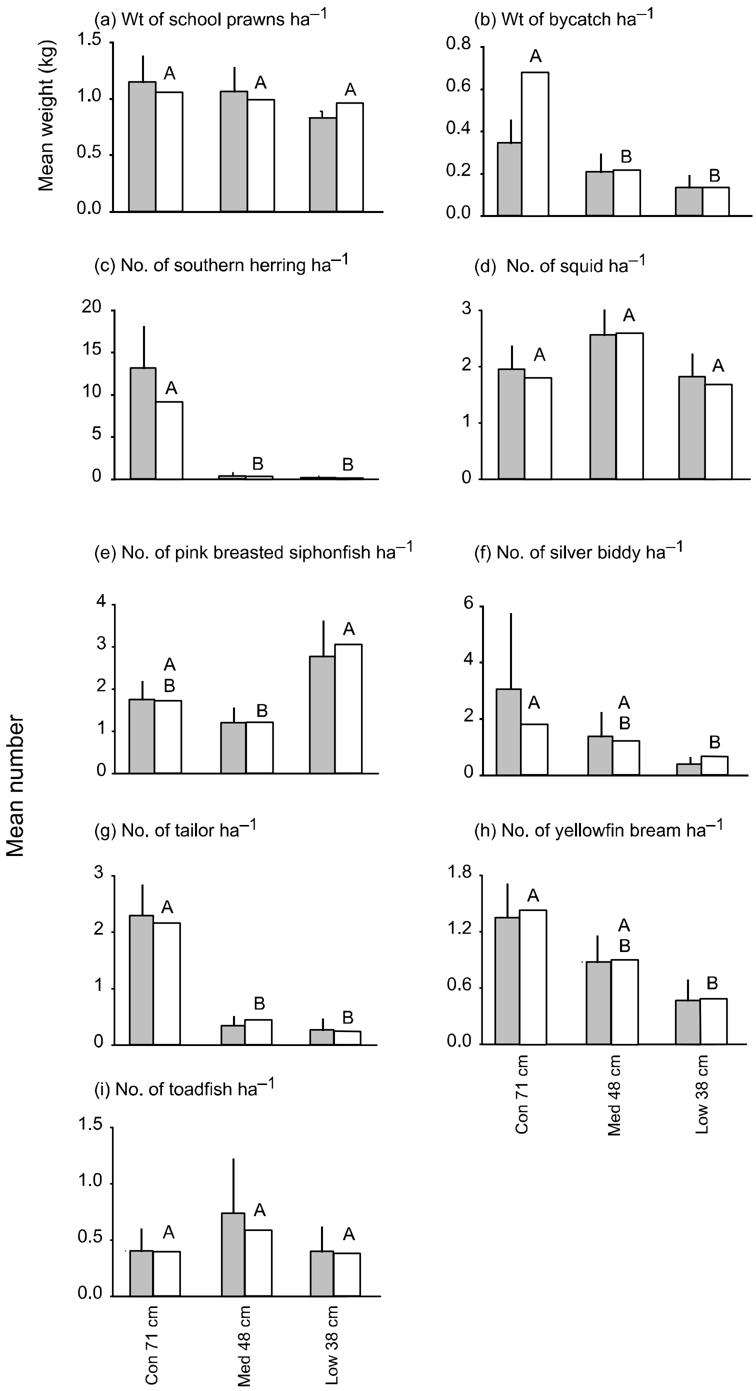
A total of 14 deployments of each headline height configuration was done, with seven paired comparisons of each of the three possible combination of configurations. It took ~1 minute to change headline heights among trawls and deployments.

There were no effects of headline height on the absolute or standardised (ha^{-1}trawled) numbers or weights of School Prawns (Fig. 5a,b). However, there was a trend for the trawl with the conventional headline height to catch more School Prawns (for both predicted absolute and standardised mean weights and numbers) by ~ 1.1 to 1.2 × that caught by the lower heights (Fig. 5). There were no significant differences in the catches of School Prawns for any of the length classes represented (4-25 mm CL) and for any comparison of headline heights.

The quantities of fish species caught showed very distinct and, for all but two, statistically significant differences due to headline height (Fig. 5). Irrespective of absolute or standardised catches, compared to trawls fished at the conventional headline height, those with the medium and low heights retained similarly and significantly less weights (by 69 and 79%, respectively) and numbers (by 57 and 66%) of total bycatch and numbers of Southern Herring *Herlotsichthys castelnaui* (by 81 and 81%) and Tailor *Pomatomus saltatrix* (by 81 and 84%) (Fig. 3b,c,g). For Silver Biddy *Gerres subfasciatus* and Yellowfin Bream *Acanthopagrus australis,* there were no differences in absolute or standardised numbers between the trawls rigged at the conventional and medium headline heights (Fig. 5f,h) but fewer in the lower headline trawl (Fig. 5f,h) (by 53 and 64%, respectively).

The only species that showed a different result was the Pink-Breasted Siphonfish *Siphamia roseigaster* (ha^{-1} trawled) where there were significantly more caught when trawls were rigged at the lowest headline height (Fig. 5e). Catches of Toadfish *Tetractenos glaber* and Squid *Uroteuthis* sp. were not significantly affected by headline height (Fig. 5d,i).

Fig. 5 - Differences in raw (+SE) and predicted mean catches trawled ha^{-1} between trawls configured at the conventional (con; 71 cm) and medium (48 cm) and low (38 cm) headline heights for the weights of (a) SchoolPprawns, *Metapenaeus macleayi* and (b) bycatch, and the numbers of (c) Southern Herring, *Herklotsichthys castelnaui*, (d) Squid, *Uroteuthis* sp., (e) Pink Breasted Siphonfish, *Siphamia roseigaster*, (f) Silver Biddy, *Gerres subfasciatus*, (g) Tailor, *Pomatomus saltatrix*, (h) Yellowfin Bream, *Acanthopagrus australis*, and (i) Toadfish, *Tetractenos glaber.* Dissimilar letters above the predicted means indicate significant differences detected in false-discovery-rate pairwise comparisons ($p < 0.05$).



Discussion

The results of this study confirmed the utility of anterior modifications for improving prawn-trawl selectivity without affecting targeted catches. Specifically, both SAFE configurations tested and lower headline heights, maintained catches of School Prawns while reducing the overall bycatch of fish (even though there were a few, relatively minor, species-specific differences); a result comparable to other, more complex trawl modifications, including traditional BRDs in codends. Furthermore, the quickly adjustable system we used to lower headline height allowed us to easily move from one configuration to another without affecting trawl performance.

While the SAFE concept was verified in this study, the double-concave version did not substantially improve the selectivity of the tested penaeid trawl. In Melli et al. (2018), the efficiency of a similar device was strongly length-dependent for roundfish species, with bigger individuals being more affected. This was attributed to physical differences in swimming ability (Wardle, 1983). In the present study, however, there was no such length-dependency for the species analysed, possibly due to either the different trawl designs and rigging (e.g. European Nephrops trawls vs Australian prawn trawls), small length ranges caught or confounding environmental effects such as noise from the vessel, dirty water, the shallowness of the lake and/or the proximity of the SAFE to the trawl mouth. Given the above result, and because simple BRDs are more likely to be adopted by fishers than more complex ones, we suggest that the single-concave SAFE is currently a better anterior configuration available for reducing bycatch in this fishery than the double concave version.

Even though the numbers of fish we encountered in the headline height experiment were low, it would appear that some fish in this system occur higher in the water column (or are herded there by the approaching trawl) than other fish and the bottom-dwelling School Prawns and therefore avoid entering the net when the headline is lowered. Although adjusting headline height could have a broad applicability in many prawn trawl fisheries, it is important to note that there are various technical and environmental conditions to take into consideration when developing this concept. Firstly, the trawl gear we used did not have any headline floats or kites; and fisheries that use these may not see the same magnitude of reductions observed here due to confounding effects of maintaining buoyancy of the headline – although, intuitively, such fisheries may realise species-selectivity benefits simply by removing such devices. Secondly, the trawl design we used did not have any lead-a-head in the top panel of netting, and the bycatch reduction we observed due to lowering the headline may be affected when a lead-a-head is used. Also, weather conditions and in particular current intensity and direction could affect the stability of the otter boards after lowering the attachment points of the headline. Finally, the shallow nature of the lake in which the experiment was done may have had some influence on fish escaping over the headline, so further work should examine the effects of headline height in deeper water fisheries.

Notwithstanding the above, because changing headline height was shown to be a relatively simple process, such a modification provides a mechanism by which prawn fishers can easily adapt their gear according to the relative abundance of fish in fishing grounds. That is, it should be simple for fishers, in areas/times of large quantities of unwanted fish, to simply lower the headline by changing their attachment points on the otter boards—and so decrease fish catches. Furthermore, compared to more conventional BRDs (placed in or near the codend), changing headline height to avoid fish has the added advantage of not having fish enter the trawl at all, thus preventing any mortalities associated with interacting with trawl components and escaping through such devices. Whilst some fishers may think that fewer school prawns would be caught using lower headline heights, any such losses should be more-than-compensated by improved species selection, less damaged prawns in catches, less time spent sorting, and therefore more time spent fishing. In particular, this modification should have significant utility in avoiding the triggering of closures to fishing due to bycatch cap limits.

Conclusions

The collaboration with DTU Aqua that involved the hosting of Ms Melli at Coffs Harbour was a substantial success in establishing a relationship between Australia' gear technologists and one of the most important gear technology groups in the world. This places Australia in a good position to learn of new European efforts in bycatch reduction as the discard ban is implemented. The project clearly promoted a very useful cross-fertilisation of various gear concepts and analytical treatments of the data collected between European and Australian team members. Further, the presence of the highly trained PhD student allowed us to continue to test anterior modifications to prawn trawls. The rapid production of research and two scientific papers that occurred in this project illustrates the value of assembling a team of similarly dedicated researchers.

Notwithstanding the success of this collaboration, because of fishery-specific anomalies, characteristics, operations, species and environmental conditions, we conclude that anterior trawl modifications should always be developed on a fishery-by-fishery basis. This point was evident here as the lack of clear bycatch reductions using the FLEXSELECT-type modification to the SAFE. Clearly, what works very well in one fishery (e.g. the FLEXSELECT in European Nephrops-trawl fisheries) does not always offer the same benefits in another fishery. It is rarely (if ever) possible to simply transfer one device from one fishery to another without substantial time spent adjusting and refining modifications.

This project has reiterated the utility of the previously developed SAFE for reducing bycatches in the Clarence River fishery—even though the new concave arrangement did not out-perform the original. However, the headline height work revealed a way that fishers can easily modify their gear to reduce fish bycatch and so avoid exceeding bycatch cap limits that may trigger closures to fishing.

Implications

The development of a relationship with DTU Aqua in bycatch reduction work provides Australia with a new source of expertise in this field at a time when Australia's jurisdictions are (unfortunately) reducing work in this area. And the various gears tested confirm the (i) utility of the SAFE as a modification that can reduce bycatches in one prawn fishery without loss of prawns and (ii) the value of quickly adjusting headline height to reduce the bycatch of small fish in places and times when their abundance may trigger fishing closures.

Recommendations

We recommend ongoing communications between the PI, NSW DPI's scientists and other gear technologists in Australia with DTU Aqua's scientists to develop more opportunities that may arise to work together in this field.

Notwithstanding this new collaboration, it is also important that Australia tries to maintain its local expertise and ongoing research and development capacity in this field to not only refine existing designs and concepts (like changes to the SAFE and reducing headline height via simple techniques), but also to produce new and innovative bycatch reduction technologies.

Further Development

In terms of gear development, this project has refined certain gear modifications (the SAFE and adjustments to headline height) that can be used by fishers to reduce bycatches whilst maintain catches of prawns.

Future research should:

(i) examine modifications to the existing SAFE design to minimise its effect on spread and enhance its capacity to facilitate fish-escape responses, perhaps by using different materials (e.g. banners) and/or light;

(ii) test the impacts of lowering headline height in other, deeper-water prawn fisheries, with and without headline floats and lead-a-head netting in the top panel;

(iii) continue to examine the utility of these and other designs in other prawn fisheries at night, offshore and in the tropical north via formal experimentation but also by industry using more streamlined approval processes than those currently available; and

(iv) a greater focus should occur on developing easily implemented solutions like changing headline height to allow fishers to be more flexible and adaptive in trying to reduce unwanted bycatches *in situ*.

Extension and Adoption

By using well-regarded local prawn-trawl fishers and their vessels, we were able to directly illustrate the potential of the modifications to the Clarence River fleet—the largest estuarine prawn-trawl fleet in Australia. These fishers are now liaising with others in the fleet about the results.

We have also incorporated the results from the work into our other current project, "Disseminating existing bycatch reduction and fuel efficiency technologies throughout Australia's prawn fisheries" (FRDC 2017/065) and are showcasing the results at the 12 workshops being held throughout the prawn trawl fishing fleets of Australia. This is leading to the further sharing of the results as workshop attendees discuss the information with their colleagues in each port.

Our scientific papers will ensure dissemination of the work to the broader scientific community. The involvement of the DTU Aqua will also see the work distributed throughout Europe where the implementation of the landings obligation policy has many jurisdictions seeking the sort of information obtained from this project

Project material Developed:

Appendix 1 – Draft manuscript 1 "Refining a simple anterior fish excluder (SAFE) for penaeid trawls"

Refining a simple anterior fish excluder (SAFE) for penaeid trawls

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Abstract

Following a renewed international interest in anterior modifications to active gears as a means for precluding unwanted captures and mortalities, promising ‘simple anterior fish excluders’ (SAFEs) comprising wire and/or plastic banners were further developed using a counter-herding concept to stimulate teleost escape in front of Australian penaeid trawls. We tested a conventional penaeid trawl against those rigged with two SAFEs comprising either single- or double-concave orientations. Both SAFEs significantly and similarly reduced absolute and standardised (ha^{-1} trawled) total bycatches (by up to 52%) and most unwanted species (especially southern herring, *Herklotsichthys castelnaui*; by up to 59%), without affecting the absolute or standardized catches of targeted penaeid*, Metapenaeus macleayi.* The results reiterate the generic utility of counter-herding devices for reducing bycatch and maintaining function across different geometries. We conclude that owing to its simplicity, a single concave SAFE might be a preferable configuration for penaeid-trawl fisheries, but other variations warrant future research.

Introduction

Globally, penaeid-trawls are associated with poor selectivity, having one of the highest bycatch rates and associated discard mortality among fishing methods (Alverson et al., 1994; Kelleher, 2005; Broadhurst et al., 2006). Historically, to address the issue, many countries have developed and mandated bycatch reduction devices (BRDs) in trawls, which are typically inserted in, or near, the codend and designed to exclude unwanted species according to different sizes, shapes and/or behaviours (Broadhurst, 2000). While many BRDs are effective, there is at least some unaccounted mortality associated with organisms entering a trawl, colliding with meshes and being selected at the codend (Broadhurst et al., 2006).

Ideally, selection would occur before animals enter trawl, since intuitively this would virtually eliminate unaccounted fishing mortality (Broadhurst et al., 2006). Although there are few studies investigating such so-called ‘anterior modifications’, the available work implies the potential for dramatic improvements and/or cumulative benefits (with posterior BRDs) in species selection (reviewed by McHugh et al., 2017). For example, substantial improvements in penaeid-trawl selectivity have been observed simply by varying conventional spreading mechanisms (Broadhurst et al., 2012), sweep lengths (McHugh et al., 2014), headline heights (Johnson et al., 2008) and/or ground gears (Broadhurst et al., 2015).

Beyond modifying the existing components of trawls, are retroactively fitted modifications designed to evoke stimuli in some fish, thus increasing their chances of avoiding capture (Ryer, 2008; McHugh et al., 2014; 2015).; Melli et al., 2018). Specifically, McHugh et al. (2014; 2015) demonstrated that a so-called ‘simple anterior fish excluder’ (SAFE) comprising wire or concave-shaped canvas sections between beams and otter boards reduced unwanted catches of southern herring (*Herklotsichthys castelnaui*), tailor (*Pomatomous saltatrix*), and sea mullet (*Mugil cephalus)* by up to 48%, with no effect on standardized catches of the targeted school prawns, *Metapenaeus macleayi* (McHugh et al., 2015).

Similar ‘counter-herding’ devices have been proposed for other fisheries (Watson et al., 1993) and more recently, following the suggestions of Ryder (2008), Melli et al. (2017) demonstrated that an anterior device configured to assume a ‘reverse ‘V’ successfully reduced teleost bycatch in a *Nephrops* (*Nephrops norvegicus*) trawl fishery in the Skagerrak Sea. McHugh et al., (2015) also concluded that this latter concept could be simply applied to the SAFE by configuring it with two smaller concave shapes directed outwards. Our aim here was to test the utility of such a double-concave configuration, by comparing it to the existing SAFE and a conventional trawl. The work was done in a shallow-water Australian estuarine trawl fishery (chosen to facilitate visual observations the gear), but the results have broader implications among penaeid-trawl fisheries worldwide (Broadhurst, 2000).

2. Materials and methods

The experiment was done in Lake Wooloweyah, Australia in a shallow-water estuarine trawl fishery, chosen to facilitate visual observations and control over the geometry of the gear. We used a double-rigged trawler (10 m and 89 kw) fishing across sandy and muddy substrata in 1–2 m of water. The trawler had two hydraulic deck winches with 10-m bridles (stainless steel wire) attached to paired flat-rectangular otter boards (1.2 m × 0.6 m; 0.72 m^2 100-mm base plates; and 53 kg in air) on each side that spread conventional Clarence River trawls (with 2.89 m sweeps).

Each trawl comprised nominal 41-mm mesh (stretched mesh openings—SMOs) throughout, 1N3B body tapers, rolled rope ground gear with lead weights, an extension section (100 T × 30 N of 40 mm mesh; with 28-mm bar spaced Nordmøre-grids installed) and codend (120 × 75 B; made from 27-mm mesh hung on the bar). Prior to fishing, 20 replicate measurements of stretched mesh openings were recorded for each trawl body, extension and codend using a purpose-built net measurer (to the nearest 0.1 mm). During fishing, Notus monitoring sensors were attached at each wing end to measure the spread (providing 20 replicates per haul) while a Lowrance global positioning system (GPS) was used to record the distance trawled and speed across the ground (SOG).

2.1. Treatments, experimental design and data collection

Two identical SAFEs were constructed from 1.50-mm Ø wire (7.25 m long with attachments) sheathed in a 255-mm wide plastic banner that was 6.40 m long and had four vertical cuts in the trailing edge to minimise hydrodynamic lift (Fig. 2). One SAFE was rigged so that it could be pulled forward approximately 1.5 m by a 4-mm Ø polyethylene rope (with a 2.4 kg weight clipped at the centre) back to the towing point to form two (double) concave shapes, while the other was left as a single-concave configuration (Fig. 2b).

The trawls with either version of the SAFE were tested against a control trawl (i.e. no SAFE) in alternate, simultaneously paired deployments. Irrespective of their treatment, the two trawls were swapped from side-to-side each day after the first three deployments.

For each deployment, technical data were collected including the total distance towed (obtained from the plotter and net monitoring system), speed over the ground (SOG), and the average wing-end spreads (based on 20 measurements). Biological data included the total weights of school prawns and bycatch, the numbers of each bycatch species, and total lengths (TL in mm to the nearest 0.5 cm) of the teleosts. For abundant teleost species, subsampling was sometimes necessary and the sampling factor was obtained dividing the number of individual length-measured by the total. Random samples of school prawns were placed into plastic bags and transferred to the laboratory, where 100 individuals were measured (carapace length – CL to the nearest 1 mm) and weighed. The length distributions, implemented by the use of a length-weight relationship (Broadhurst et al., 2006), were used to estimate the total number of school prawns caught.

2.2. Data analyses

Prior to starting the work, a linear model (LM) was used to test the null hypothesis that there were no differences in the mesh sizes of each trawl, extension or codend. Data describing engineering and catch variables were analysed in linear mixed models (LMM) with 'anterior configuration' considered fixed, while 'trawls', 'sides' and 'days' and the interaction between 'deployments' and days were included as random terms. Engineering variables were analysed raw. Speed across the ground was considered as a covariate in the LMM for wind-end spread and assessed based on the lowest value for Akaike information criterion (Akaike, 1974). Catches were considered both as (1) absolute and (2) standardized to ha^{-1} trawled using the swept area of the trawl (calculated by average wing-end spread × distance trawled). In both cases, data were log-transformed so that differences between gears were modelled to act multiplicatively. The significance of gear configuration was determined using a Wald *F*-test and any significant differences were subsequently explored using the Benjamini-Hochberg-Yekutieli procedure to control the false discovery rate (FDR).

For those species caught in sufficient quantities, we conducted a length-dependant catch-comparison analysis (SELNET; Herrmann et al., 2012), following the methodology of Krag et al. (2015) and including recent model improvements developed by Herrmann et al. (2017). One thousand bootstrap repetitions were performed to calculate the Efron 95% CI (Efron, 1982) for the modelled catch comparison curve using a double bootstrap method (Millar, 1993). The quality of model fits was assessed on the basis of the fit-statistics: *p*-value, deviance and degrees of freedom. In particular, a *p*-value below 0.05 expressed a significant residual variation between the fitted model and the experimental data, suggesting potential structural problems in the model or overdispersion in the data (Wileman et al., 1996). Any significant residual variation was explored to determine whether the model could be trusted to describe the experimental data.

Because the catch comparison rate expresses the probability of catching an individual of length *l* in the test trawl given that it was caught in either trawl, a catch comparison rate of 0.5 indicates the two trawls were functioning equally (Krag et al., 2014). However, according to Melli et al. (2017) we corrected this baseline for equality from differences in spread by calculating:

$$cc_0 = \frac{\sum_{j=1}^{h} ST_j}{\sum_{j=1}^{h}(ST_j + SC_j)} \qquad (1)$$

where STj and SCj are the averaged wings-end spreads for the test and control trawls in each deployment *j*. Where the Efron 95% CIs of the catch comparison curve did not include cc_0, there was a significant difference between the two trawls caused by the gear configuration (i.e. anterior device).

3.0 Results

The SMOs were not significantly different between trawls, extensions or codends, with overall means (±SE) of 41.25 ± 0.08, 41.40 ± 0.17 and 27.35 ± 0.10 mm, respectively (LM, $p > 0.05$). A total of ten replicate paired diurnal deployments of trawls with each SAFE were done against the control at 1.32–1.43 m s^{-1}, over distances of 3.17–3.43 km.

The distances trawled were not significantly different among configurations (LMM, $p > 0.05$), but wing-end spread (LMM was reduced to the fixed effect of trawl configuration only) and therefore area trawled were (LMM, $p < 0.001$, Table 1).). False-discovery-rate pairwise comparisons revealed the control trawl was spread significantly wider (4.11 ± 0.04 m) and consequently trawled a greater area (1.35 ± 0.02 ha) than the test trawls with the single- (3.59 ± 0.05 m and 1.18 ± 0.02 ha) or double-concave SAFE (3.66 ± 0.05 m and 1.20 ± 0.02 ha; $p < 0.001$; Table 1). There was no difference between the two SAFE configurations for these variables (FDR, $p > 0.05$).

In total, catches comprised 140 kg of school prawns (59,843 individuals) and 60 kg of bycatch (5,889 individuals) (Table 2. Among the species caught, school prawns were dominant (92% of catches by number), while seven species (of 18 in total) comprised 99% of the total fish bycatch, and formed the basis of biological analyses (Table 2). Linear mixed models did not detect any significant differences between anterior configurations for either the absolute or standardized (i.e. ha^{-1} trawled) weights or numbers of school prawns ($p > 0.05$; Table 2, Fig. 3a and b). A significant effect of anterior configuration was detected for both the absolute and standardized numbers and weights of bycatch, of southern herring, *Herklotsichthys castelnaui* and pink breasted siphonfish, *Siphamia roseigaster* (LMM, $p < 0.01$; Table 2, Fig. 3 e–h).

False discovery-rate-pairwise comparisons revealed that trawls rigged with the single- and double-concave SAFE similarly and significantly ($p<0.05$) reduced the absolute and standardized numbers of southern herring by up to 50 and 59%, respectively (Fig. 3e and g). Because southern herring was one of the most abundant species, these reductions manifested as comparable effects on the weights and numbers of absolute and standardized total bycatch (by up to 52%; FDR, $p < 0.05$; Fig. 3c and d). Conversely, the least abundant analysed species, pink breasted siphonfish, was retained in significantly greater absolute (by up to 3.8×) and standardized numbers (4.0×) in trawls with either SAFEs than in the control (FDR, $p < 0.05$; Fig. 3g and h).

Four fish (southern herring, forktail catfish, toadfish and tailor) and school prawns were analysed using the catch comparison analysis (Table 3). Of the 12 models obtained, most had good fit statistics with p-values >0.05 (Table 3). Three models had poor fit statistics ($p < 0.05$, deviance >> DoF): the models for forktail catfish and toadfish in the single-concave SAFE comparison and the model for school prawns in the double-concave SAFE comparison. For these cases the residual deviations between the data and the modelled curves were investigated but no systematic structure was detected. We considered the low p-values to be a consequence of overdispersion in the data caused by sub-sampling (e.g. forktail catfish and school prawns) and the high dispersion in those length classes with relative low frequency.

Similar to the results obtained with the LMM, the SAFEs did not significantly affect catches of the targeted school prawns for any of the length classes represented (Fig. 4). Compared to the conventional trawl, those with either SAFE caught significantly less southern herring of 7-9.5 and 8-12.5 cm with the single- and double-concave SAFE, respectively (Fig. 4). Tailor and toadfish were affected by the double-concave SAFE but only for few length classes (10.5-12.5 and 11-11.5 cm for tailor and toadfish, respectively; Fig. 4). No effect was detected on the catch of forktail catfish in either experiment.

4. Discussion

The results of this study confirm the broad utility of anterior modifications in general for improving penaeid trawl selectivity without affecting targeted catches (reviewed by McHugh et al., 2016) and the specific effectiveness of counter-herding devices like the SAFE (McHugh et al., 2014; 2015). Specifically, both SAFE configurations tested here maintained the absolute and standardized catches of school prawns while reducing the overall bycatch of fish (by >50%); a result comparable to other, more complex trawl modifications, including traditional BRDs in codends (reviewed by Broadhurst, 2000).

However, there clearly were divergent species-specific responses and changes to trawl selectivity which might have been caused not only by the SAFEs, but their concomitant engineering consequences for trawl geometry. These effects warrant consideration and, as a starting point, it is first necessary to postulate the likely confounding effects of the observed significant changes in SR between trawls rigged with the SAFEs and without (Broadhurst et al., 2014). The single-concave SAFE and trawl designs used here were exactly the same as those tested by McHugh et al. (2015), but we recorded a much larger reduction in wing-end spread (5 v 13%); a result reflecting the skippers choice to use smaller otter boards here (0.75 m^2) than previously (0.81 m^2; McHugh et al., 2015). Also, adding the towing rope to the double-concave SAFE configuration only marginally improved wing end-spread (to an 11% reduction for the conventional configuration).

In previous work, Broadhurst et al. (2014) hypothesised that the lateral tension evoked by reduced spread in penaeid trawls likely (i) improves ground contact, (ii) increases headline height, and (iii) reduces the angles of netting panels in the trawl body; all of which can offset the concomitantly lower wing-end swept area and so affect catches. Similar results have been postulated for fish trawls subjected to varying spread (Rose and Nunnallee, 1998; von Szalay and Somerton, 2005). Such compensatory changes to trawl geometry and selectivity may explain why, despite a reduction in swept area with the SAFEs, the absolute catches of school prawns were maintained. More specifically, following the technical outcomes suggested above for lower spreads, perhaps more school prawns were stimulated from the lake bed, fewer were able to escape over the headrope and/or those that entered the trawl encountered shallower netting panels with less opportunity to escape as they were directed to the codend.

Similarly, the significantly greater catches of pink breasted siphonfish using the SAFEs may also be explained by the latter effects because, like prawns, this species is very small and consequently a weaker swimmer than larger teleosts (Wardle, 1989). In contrast, the large reductions in catches of southern herring in the trawls rigged with the SAFEs were more likely caused by the associated visual or tactile stimuli provided by the SAFEs than any changes in spread, simply because most of geometric changes mentioned above should, if anything, herd more fish into the trawl, partly negating some of the effectiveness of the SAFE (Broadhurst et al., 2014; McHugh et al., 2014; 2015). The results were consistent with those obtained by McHugh et al. (2015) and, while there was some evidence of slightly greater reduction in numbers of southern herring by the double-concave SAFE, the impacts were minimal.

Unlike for southern herring, we failed to detect any significant reduction in catches of tailor observed by McHugh et al. (2015) for the single-concave SAFE. A speculative explanation might be that the reduction in spread caused a deeper concave and so reduced efficiency, although clearly this was not the case for southern herring. One clear inter-experimental difference was the abundance of tailor, whereby McHugh et al. (2015) caught ~28 individuals control deployment^{-1} vs only ~3 control deployment^{-1}in the present study. Such a difference in density may be important, because studies have shown that larger schools of fish can collectively respond to visual or tactile stimuli more rapidly than individuals (Parrish, 1999). Nevertheless, other potential differences between the experiments in environmental parameters (e.g. turbidity and available light) preclude a definitive explanation of this result.

In conclusion, while the SAFE concept has been verified in this study, the double-concave version did not substantially improve the selectivity of the tested penaeid trawl. In Melli et al. (2018), the efficiency of geometry similar device was strongly length-dependent for roundfish species, with bigger individuals being much more affected, and attributed to physical differences in swimming ability (Wardle, 1983). In the present study, there was no such length-dependency for the species analysed, possibly due to either the small length ranges caught or alternativelyconfounding environmental effects such as noise from the vessel, dirty water and the proximity of the SAFE to the trawl mouth.

Given the above result, and because simple BRDs are more likely to be adopted by fishers than more complex ones (Broadhurst, 2000), we suggest that the single-concave SAFE is currently the best anterior configuration available for reducing bycatch in this fishery without negatively impacting target catches. Future research should examine modifications to the existing SAFE design to minimise its effect on spread and enhance its capacity to facilitate fish escape responses, perhaps by using different materials (e.g. banners) and/or light, which have proven successful in similar fisheries (Hannah et al., 2015). Such work is warranted, because bycatch issues remain dynamic among penaeid fisheries and rarely (if ever) solved via one single modification or approach.

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Table 1

Summaries of Wald *F* statistics from linear mixed models (LMM) assessing the importance of the fixed effect of trawl configuration (control with no SAFE vs single- and double concave SAFEs) for explaining variability among technical and biological responses, and predicted means (and SEs where appropriate). All numbers and weights (kg) were log-transformed and analysed as absolute and standardized to ha^{-1} trawled. Random effects included 'trawls', 'sides of the vessel', 'days' and 'deployments within days' for all LMMs, and also 'paired trawl sensors' for those LMMs assessing relevant technical variables.

Technical variables	Wald *F*	Control	Single-concave SAFE	Double-concave SAFE
Wing-end spread (m)	51.40***	4.11 (0.04)	3.59 (0.05)	3.66 (0.05)
Distance trawled (km)	0.06	3.28 (0.02)	3.29 (0.03)	3.28 (0.03)
Area trawled (ha)	52.99***	1.35 (0.02)	1.18 (0.02)	1.20 (0.02)
Biological variables				
Wt of school prawns	0.08	5.38	5.59	5.33
Wt school prawns ha^{-1}	1.75	4.01	4.77	4.46
No. of school prawns	0.54	2370.39	2244.58	2579.14
No. of school prawns ha^{-1}	2.07	1765.75	1915.05	2155.60
Wt of total bycatch	13.70***	2.00	1.40	0.96
Wt of total bycatch ha^{-1}	8.98**	1.48	1.19	0.80
No of total bycatch	6.83**	178.43	121.26	100.65
No. of total bycatch ha^{-1}	4.08*	132.61	102.71	84.42
No. of forktail catfish	1.16	55.06	105.32	92.04
No. of forktail catfish ha^{-1}	1.39	40.09	79.17	67.34
No. of southern herring	13.76***	83.86	46.84	34.07
No. of southern herring ha^{-1}	9.88***	62.27	39.80	30.95
No. of toadfish	1.58	10.08	9.49	6.57
No. of toadfish ha^{-1}	1.18	7.18	7.43	6.07
No. of tailor	1.12	5.15	3.96	3.54
No. of tailor ha^{-1}	0.59	3.73	3.14	3.86
No. of pink breasted siphonfish	7.43**	1.34	3.19	5.16
No. of pink breasted siphonfish ha^{-1}	8.23**	1.04	2.65	4.17
No. of yellowfin bream	0.08	2.29	2.56	2.32
No. of yellowfin bream ha^{-1}	0.31	1.72	2.07	1.90
No. of silver biddy	1.34	1.24	0.70	0.70
No. of silver biddy ha^{-1}	1.00	0.94	0.57	0.59

***$p < 0.001$; **$p < 0.01$; *$p < 0.05$

Table 2

Scientific and common names, numbers and sizes of organisms (in ascending order of abundance) caught during the experiment, with the number measured in parentheses (or else all lengths were recorded). Sizes were CL in mm for school prawns and TL in cm for fish.

Scientific name	Common name	Numbers	Size range
Metapenaeus macleayi	School prawn	65 789 (1963)	4–-25
Arius graeffei	Forktail catfish	2647 (734)	6–-10.5
Herklotsichthys castelnaui	Southern herring	2502 (2374)	4–-16
Tetractenos glaber	Toadfish	300	6.5–-16
Pomatomus saltatrix	Tailor	151	6.5–-14.5
Siphamia roseigaster	Pink-breasted siphonfish	106	2–-6.5
Acanthopagrus australis	Yellowfin bream	96	6.5—-24
Gerres subfasciatus	Silver biddy	39	5.5–-14
Engraulis australis	Australian anchovy	7	4.5–-7
Pseudocaranx dentex	Silver trevally	7	4.5–-13
Dasyatis sp	Stingray	6	–-
Mugil cephalus	Bully mullet	4	5–-16.5
Enoplosus armatus	Old wife	2	7–-8
Muraenesox bagio	Common pike eel	2	–-
Platycephalus fuscus	Dusky flathead	2	19.5–-21
Ambassis marianus	Ramsey's perchlet	2	9–-9.5
Rhabdosargus sarba	Tarwhine	2	6.5–-9
Pseudorhombus arsius	Largetooth flounder	1	13
Hyporhamphus regularis	River garfish	1	13.5

Table 3

Deviances, significance and degrees of freedom for converged relative selectivity models among key species caught.

Trawl	Deviance	DF
Single concave		
School prawns	18.24	15
Forktail catfish	19.45	14
Southern herring	14.37*	5
Tailor	11.20	9
Double concave		
School prawns	27.49*	15
Forktail catfish	21.82	13
Southern herring	6.01	3
Tailor	2.93	8

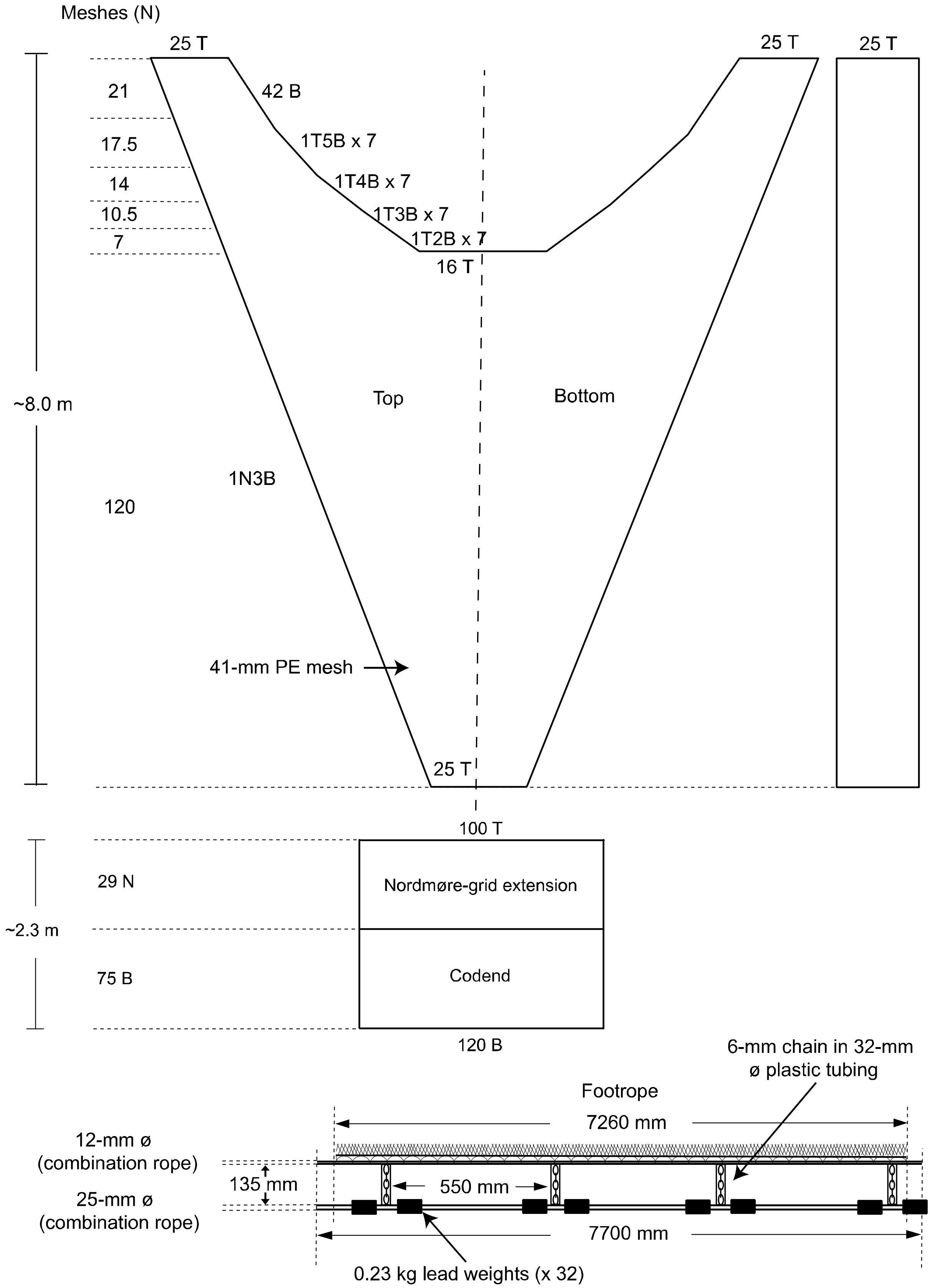
Captions to Figs.

Fig. 1. Plan of the conventional trawls used in the experiment.

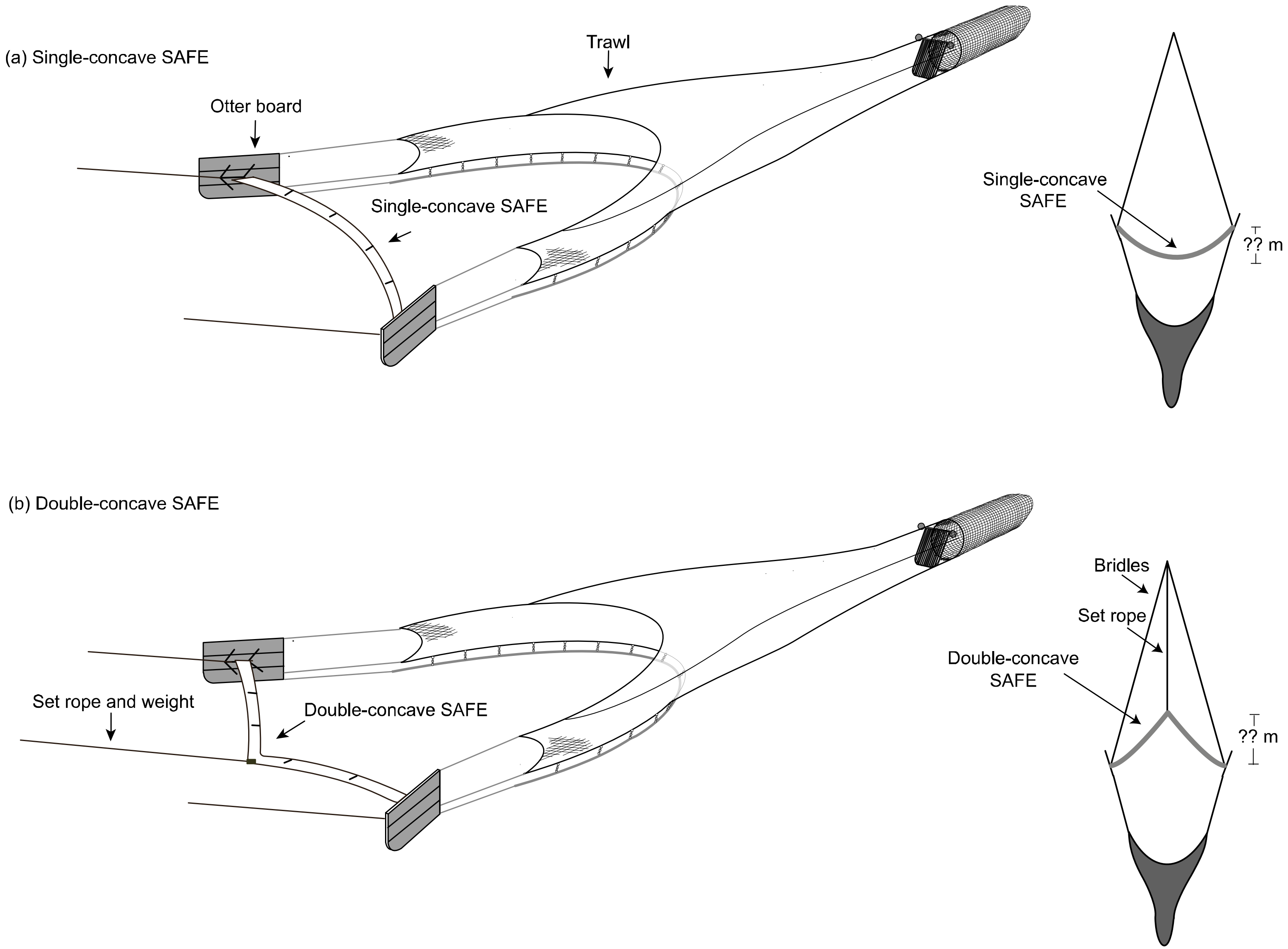
Fig. 2. Three and two-dimensional diagrams of the (a) single-concave and (b) double-concave SAFEs attached to the penaeid trawl.

Fig. 3. Differences in raw (+SE) and predicted mean catches between trawls without (control) the simple anterior fish excluder (SAFE) and those with a single- and double-concave SAFE for the (a) absolute and (b) ha $^{-1}$ trawled weights of school prawns, *Metapenaeus macleayi*, (c) absolute and (d) ha $^{-1}$ trawled weights of bycatch and the numbers of (e) absolute and (f) ha $^{-1}$ trawled southern herring, *Herklotsichthys castelnaui* and (g) absolute and (i) ha $^{-1}$ trawled pink breasted siphonfish, *Siphamia roseigaster*. Dissimilar letters above the predicted means indicate significant differences detected in false-discovery-rate pairwise comparisons ($p < 0.05$).

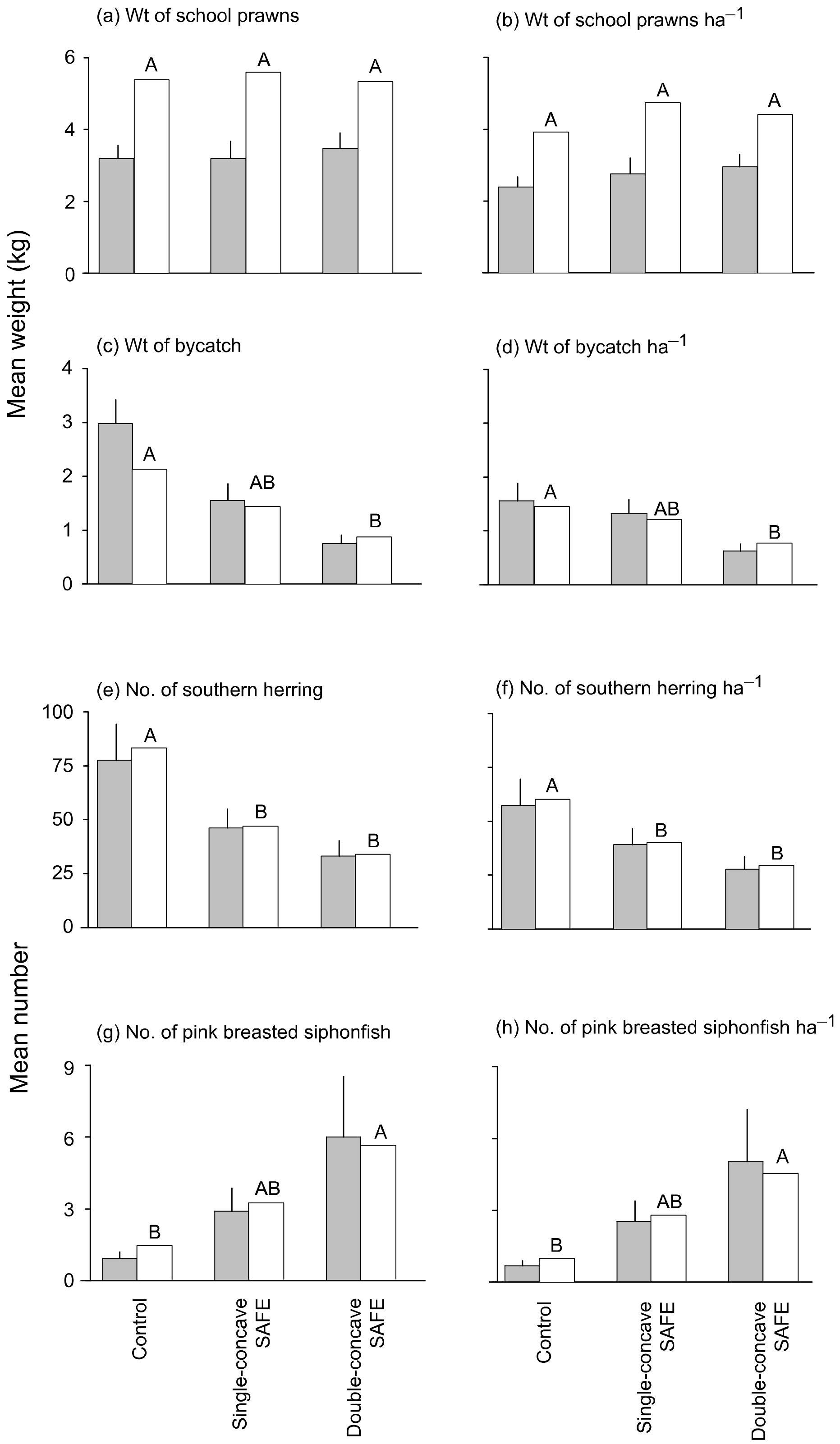
Fig.4. Catch comparison curves of trawls with the single- and double-concave SAFEs respect to the control trawl of the target school prawns, *Metapenaeus macleayi*, and three of the fish species analysed. The curves (solid lines) represent the modeled catch efficiency fitted to the experimental points (dots). The dashed horizontal lines indicate the baseline for no difference in catch efficiency between the trawls. The shaded areas represent the 95% confidence intervals while the dot-dashed lines depict the underlying size frequencies.



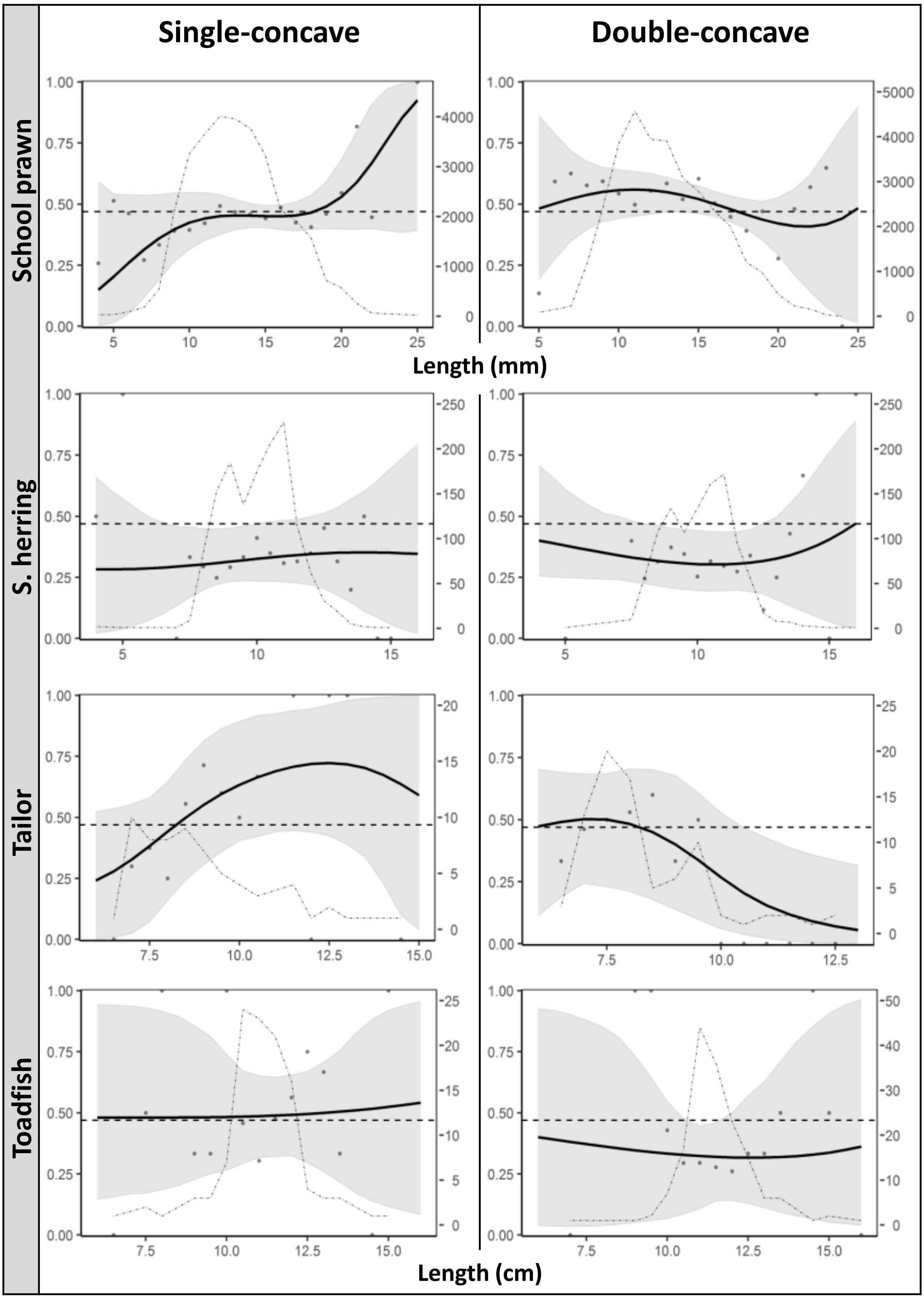
Meshes (N)
25 T
25 T
25 T
21
42 B
17.5
1T5B x 7
14
1T4B x 7
10.5
1T3B x 7
7
1T2B x 7
16 T
~8.0 m
Top
Bottom
1N3B
120
41-mm PE mesh
25 T
100 T
29 N
Nordmøre-grid extension
~2.3 m
75 B
Codend
120 B
6-mm chain in 32-mm ø plastic tubing
Footrope
7260 mm
12-mm ø (combination rope)
135 mm
550 mm
25-mm ø (combination rope)
7700 mm
0.23 kg lead weights (x 32)



(a) Single-concave SAFE
Trawl
Otter board
Single-concave SAFE
Single-concave
SAFE
?? m
(b) Double-concave SAFE
Set rope and weight
Double-concave SAFE
Bridles
Set rope
Double-concave
SAFE
?? m



(a) Wt of school prawns
(b) Wt of school prawns ha^{-1}
(c) Wt of bycatch
(d) Wt of bycatch ha^{-1}
(e) No. of southern herring
(f) No. of southern herring ha^{-1}
(g) No. of pink breasted siphonfish
(h) No. of pink breasted siphonfish ha^{-1}
Mean weight (kg)
Mean number
A
AB
B
0
2
4
6
1
3
25
50
75
100
9
Control
Single-concave SAFE
Double-concave SAFE



Single-concave
Double-concave
School prawn
S. herring
Tailor
Toadfish
Length (mm)
Length (cm)

Appendix 2 – Draft manuscript "Adaptive bycatch reduction in penaeid trawls via rapid headline adjustments"

Adaptive bycatch reduction in penaeid trawls via rapid adjustments to headline height

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Abstract

Penaeid trawling is among the world's least selective fishing methods which, in several fisheries, has led to spatial closures being implemented if certain bycatch caps are exceeded. Considerable work has been done to develop modifications to trawls that reduce unwanted bycatches with most focussed at, or near, the codend. But more recent efforts have examined ways to prevent bycatch entry into trawls entirely—via modifications to anterior components. This study assessed the utility of proactively lowering the headlines of Australian penaeid trawls, using clips at the otter boards, to 68 and 54% of the conventional height, and demonstrated mean total bycatch reductions (by weight) of 69 and 79%, respectively, without affecting catches of the targeted *Metapenaeus macleayi*. The results provide insights into the location and behaviour of various species in the water column as trawls approach, while

providing a simple and easy method for fishers to use *in situ* to avoid high levels of bycatch and associated fishing closures.

KEYWORDS

Bycatch reduction, penaeid trawls, headline height

1 INTRODUCTION

For several decades, efforts to reduce bycatch have usually involved researchers developing solutions that are then trialled in fisheries, modified and eventually implemented as regulations (Kennelly, 2007; McHugh et al., 2017). Such work has resulted in a plethora of bycatch reduction devices (BRDs), as well as fishing industries that have become well-versed in their benefits and applications. A more current priority is to develop modifications that allow fishers to quickly adjust gear selectivity while at sea. Such modifications would be very successful in reducing overall bycatch because they would facilitate rapid implementation according to spatio-temporal variations in catches. They could also have utility under management regimes that involve bycatch cap limits—where excessive bycatches can lead to fishing closures (Little et al., 2015).

Penaeid trawls are one of the world's least selective fishing gears, catching large quantities of non-targeted fish and other organisms; the mortality of which is considered wasteful (Alverson et al., 1994; Kelleher, 2005). Despite decades developing various operational and technical modifications to reduce bycatch and/or discard mortality (reviewed by Broadhurst, 2000; McHugh et al., 2017) significant issues remain throughout many penaeid-trawl fisheries. Most developments have involved modifications at or near the codend, comprising grids or strategically positioned panels and meshes under the (mostly untested) assumption of minimal escape mortality (for reviews, see Broadhurst, 2000; Broadhurst et al., 2006; McHugh et al., 2017). Relatively less work has focused on anterior modifications to trawls. By developing modifications that stop bycatch from entering trawls at all, escape mortalities will be prevented, presumably with concomitant benefits for stocks.

While it is well known that higher headlines in fish trawls increase the capture of some fish (Fujimori et al., 2002), only a few studies have assessed the utility of reducing headline height to decrease bycatches in penaeid trawls (e.g. Broadhurst et al., 2013; 2016). The available work demonstrates a need to achieve sufficient headline height to maximise the capture of penaeids stimulated upwards by the ground gear, whilst lowering it sufficiently to minimise catches of fish and cephalopods (Stender and Barnes, 1994; Eayrs, 2002; Madhu et al., 2015). For example, Hines et al. (1999) compared high (3.7 m) and low (0.9 m) headline heights in skimmer trawls and, while the latter caught less total bycatch (by ~14%), catches of brown shrimp, *Farfantepenaeus aztecus* were also significantly reduced (by up to 39%). In contrast, Johnson et al. (2008) observed 50% fewer fish low- (0.8 m) than high- (1.2 m) opening otter trawls, with no significant differences in catches of school prawns *Metapenaeus macleayi*—although swept area was not quantified and may have confounded comparisons. Broadhurst et al. (2016) assessed the utility of knot orientation (which affects panel lift and therefore headline height) and observed fewer standardised catches (ha^{-1} trawled) of fish (by up to 67%), but also fewer school prawns (by 26%) in the lower-height trawl.

Unlike some retroactively fitted BRDs, varying headline height can be a relatively simple procedure which, if successful in reducing bycatch whilst maintaining catches of the targeted penaeids, may provide fishers with a system to adjust their fishing practices quickly and in response to high or low abundances of problematic species. Here we assess the utility of such a system in an Australian estuarine penaeid-trawl fishery, by testing the effects of three different headline heights on bycatch and targeted penaeids.

2 METHODS

2.1 Experimental design

This study was done in Lake Wooloweyah, Australia, using a local trawler (10 m and 89 kW) fishing in ~1.5–2.0 m across sandy and mud substrata. The vessel was equipped with a Notus trawl monitoring system (to measure wing-end spread) and a Lowrance global positioning system (GPS) to record the distance trawled and speed across the ground (SOG). The trawler had 8-mm diameter (Ø) stainless warps and 10-m bridles (6-mm Ø stainless wire) on two hydraulic winches and attached to paired sets (i.e. double rig) of stainless-steel cambered otter boards (53.0 kg; 1.08 × 0.73 m; 0.79 m^2) (Fig. 1a).

Each otter board had conventional headline, ground gear and foot-rope attachment points at the trailing edges. For the experiment, we attached a 0.73-m length of 8-mm Ø chain along the trailing edge of each otter board to provide multiple attachment points (i.e. at any of the chains links) for the headline (Fig. 1b). The headline attachments included: (1) the conventional ‘high’ attachment at 0.71 cm above the ground chain; (2) a ‘medium’ attachment at 48 cm (or 68%) above the ground gear; and (3) a ‘low’ attachment at 38 cm (or 54%) above the ground gear (slightly above the midpoint of the otter board to maintain stability; Fig. 1b). Snap clips that fit through the attachment points were shackled to 2.93-m sweeps and then to the ground gears, foot-ropes and headlines of two identical and conventional trawls (Fig. 2). The trawls comprised nominal 41-mm mesh (stretched mesh opening) throughout, 1N3B body tapers and rolled-rope ground gear with lead weights (Fig. 2). All trawls were attached to extension sections (100 T × 30 N of nominal 40 mm mesh; with 28-mm bar spaced Nordmøre-grids installed) and codends (120 × 75 B; made from nominal 27-mm mesh hung on the bar).

At the start of the first day, each of the trawls was randomly assigned to a vessel side (i.e. otter-board pair) and the ground-gear and foot-rope sweeps were shackled to the otter boards (Fig. 1b). The headline heights were randomly assigned so we compared the conventional high (71 cm) against each of the medium (48 cm) and low (38 cm) headline heights, and the latter two against each other (i.e. all three possible combination of configurations) in alternate, simultaneously paired 30-min deployments and with the paired Notus trawl sensors attached at the wing ends. The trawls were always deployed using 9.9 m of bridle (i.e. within ~5 m of the vessel stern). The two trawls were swapped from side-to-side at the beginning and halfway through each trawling day, while the paired Notus sensors were swapped between trawls at the start of each day.

The technical data collected during each deployment included the total distance trawled (defined as otter boards on and off the bottom and obtained from the plotter and net monitoring system), SOG, and the averaged wing-end spreads (in m; recorded every 1 min for 15 min on alternate sides of the vessel). The depth of fishing and distance of the trawls behind the vessel remained constant. Collected biological data included the total weights of school prawns and bycatch, the numbers of each bycatch species, and total lengths (TL rounded to the lower 0.5 cm) of the teleosts. Random samples of school prawns were placed into plastic bags and transferred to the laboratory, where 100 individuals were measured (carapace length; CL rounded to the lower 1 mm) and weighed. The latter data were used to estimate the total numbers of school prawns caught during each deployment.

2.2 Data analyses

Data describing engineering and catch variables were analysed in linear mixed models (LMM) with ‘headline height’ considered fixed, while ‘trawls’, ‘Notus sensors’, ‘vessel sides’ and ‘days’ and the interaction between ‘deployments’ and days were included as random terms. Engineering variables were analysed raw. Speed across the ground was considered as a covariate in the LMM for wing-end spread and assessed based on the lowest value for Akaike’s information criterion (AIC; Akaike, 1974). Data for school prawns, total bycatch and other species caught in sufficient numbers for individual analysis were considered both as (1) absolute and (2) standardized to ha^{-1} trawled using the swept area of the trawl (calculated by average wing-end spread × distance trawled). In both cases, data were log-transformed so that differences between gears were modelled to act multiplicatively. The significance of gear configuration was determined using a Wald *F*-test and any significant differences were subsequently explored using the Benjamini-Hochberg-Yekutieli procedure to control the false discovery rate (FDR). Models were fitted using ASReml in R 2.15.3 (The R Project for Statistical Computing; http://www.r-project.org/).

To determine if lowering the headline had an effect on school prawn size-selectivity, we conducted a length-dependant catch-comparison analysis (SELNET; Herrmann et al., 2012), following the methodology of Krag et al. (2015) and including recent model improvements developed by Herrmann et al. (2017). Each combination of headline heights was analysed separately. One thousand bootstrap repetitions were performed to calculate the Efron 95% Confidence Intervals (CI; Efron, 1982) for the modelled catch comparison curves using a double bootstrap method (Millar, 1993). The quality of the model fits was assessed on the basis of the fit-statistics: *p*-value, deviance and degrees of freedom (Wileman et al., 1996).

3 RESULTS

Fourteen deployments of each headline-height configuration were done during three days, with seven paired comparisons of each of the three possible combinations of configurations. It took ~1 minute to change headline heights among trawls and deployments. Nineteen species were caught, and while catches were low, they were all within the range of conventional deployments (Table 1).

There were no significant differences in trawl wing-end spread and distance and area trawled due to reducing headline height, although the means increased slightly (LMM, $p > 0.05$; Table 2). Including SOG in the LMM for wing-end spread produced a lower AIC, but the covariate was not significant ($p > 0.05$). There were no stability problems with the otter boards attached to the lower headline heights.

There were similarly no effects of headline height on the absolute or standardized (ha^{-1} trawled) numbers or weights of school prawns (LMM, $p > 0.05$; Table 2; Fig. 3a,b). However, there was a trend for the trawl with the conventional high headline height to catch more school prawns (for both predicted absolute and standardised mean weights and numbers by ~1.1 to 1.2 × that caught by the lower heights; Fig. 3a; Tables 2 and 3).

The three modelled length-dependent catch-comparison curves fitted the experimental data (4–25 mm CL) well, and only the model for the conventional vs medium headline had poor fit statistics (p-value < 0.001; deviance = 42.29; dof = 14). After inspecting the residuals, the poor fit statistics were attributed to overdispersion in the length classes at the limit of the sampled range. We were therefore confident in applying the model. The analysis showed no significant differences in the catches of school prawns for any of the length classes represented for any comparison of headline height.

The quantities of bycatch caught showed very distinct and, for all but two, statistically significant differences due to headline height (LMM, $p < 0.05$; Table 2 and Fig. 3). Irrespective of absolute or standardised catches, compared to trawls fished at the conventional high headline height, those with the medium and low heights retained similarly and significantly less weights (predicted means reduced by up to 69 and 79%, respectively) and numbers (by 57 and 66%) of total bycatch and numbers of southern herring *Herlotsichthys castelnaui* (by 81 and 92%) and tailor *Pomatomus saltatrix* (by 81 and 84%) (LMM and FDR, $p < 0.001$; Table 2; Fig. 3b,c,g). For silver biddy *Gerres subfasciatus* and yellowfin bream *Acanthopagrus australis*, there were no differences in absolute or standardized numbers between the trawls rigged at the conventional and medium headline heights (LMM and FDR, $p > 0.05$; Table 2; Fig. 3f,h) but fewer in the lower headline trawl (LMM and FDR $p < 0.05$; Table 2; Fig. 3f,h) (by 53 and 64%, respectively).

The only species that showed a contrasting result was pink-breasted siphonfish *Siphamia roseigaster* (ha^{-1} trawled) with significantly more caught when trawls were rigged at the lowest headline height (LMM and FDR $p < 0.05$; Table 2; Fig. 3e). Catches of toadfish *Tetractenos glaber* and squid *Uroteuthis* sp. were not affected by headline height (LMM, $p >$ 0.05; Table 2; Fig. 3d,i).

4 DISCUSSION

There were two very obvious and quite positive outcomes from this experiment. First, reducing headline height reduced the bycatch of small fish without significantly affecting school prawn catches; and second, the quickly adjustable system facilitated rapidly moving the headline from one configuration to another, without affecting trawl performance.

According to the results, it would appear that some of the bycaught species in this system orientate higher in the water column (or are herded there by the approaching trawl) than others, and the mostly benthic school prawns (Ruello, 1973; Coles, 1979). Such individuals therefore avoided entering the net when the headline was lowered. More specifically, because the medium headline configuration excluded the same numbers of southern herring and tailor as the low headline, individuals of these species must have been relatively high in the water column. By comparison other fish, like silver biddies and yellowfin bream, may have been slightly lower in the water column since only the low headline reduced their numbers. Toadfish and squid, on the other hand, did not respond to either reduction in headline height and were likely either orientated closer to the bottom, or were not strong enough swimmers to respond to the trawl and rise up and over the headline.

In contrast, for the very small pink-breasted siphonfish, we detected the opposite result to that for other species with greater standardised catches in the lower headline configuration than the conventional or medium-height configurations. But this result may simply reflect the very small size of this species and its probable poor swimming ability.

Although adjustable headline heights should have broad applicability in many penaeid-trawl fisheries, it is important to note that there are various technical and environmental considerations when developing this concept. First, the trawl we used did not have headline floats or kites, and fisheries that use these may not see the same magnitude of reductions observed here due to confounding effects of maintained buoyancy of the headline—although, intuitively, such fisheries may realise species-selectivity benefits simply by removing such devices. Second, the trawl did not have any ‘lead-a-head’ (i.e. whereby the top panel extends anterior to the bottom panel), and the bycatch reduction we observed due to lowering the headline may be affected when a lead-a-head is used. Third, weather conditions and especially current intensity and direction could affect the stability of otter boards with low headline attachment points. Fourth, the shallow nature of the lake in which the experiment was done may have had some influence on fish escaping over the headline, so further work should examine the effects of headline height in deeper water fisheries. Finally, no significant increase in swept area was observed with a reduction in headline height, although the means were incrementally greater. Such a positive relationship might be expected, simply because a lower angle of netting would reduce drag and allow the trawl to open wider. Under some circumstances, this could affect catches of penaeids (Broadhurst et al., 2015; 2016).

Notwithstanding the above, because changing headline height is clearly a simple process, such a modification provides a mechanism by which penaeid fishers can easily adapt their gear to avoid large abundances of particular species. Further, unlike for conventional, posteriorly located BRDs, changing headline height precludes many fish entering the trawl at all, thus preventing any associated mortalities. Whilst the possibility exists for fewer penaeids to be caught using lower headline heights, if realised, any such losses might be more-than-compensated by improved species selection precluding fishing closures, less damaged prawns in catches, less time spent sorting, and therefore more time spent fishing.

This work has shown the utility of lowering headline height on reducing bycatches of small fish in penaeid trawls and how such a modification can be used by fishers to quickly reduce such bycatches where and when teleosts are in large abundances. This could have substantial utility for avoiding fishing closures due to bycatch cap limits. We recommend that greater focus continues on developing such easily implemented solutions—and so allow fishers to be more flexible and adaptive in trying to reduce unwanted bycatches *in situ*.

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TABLE 1 Scientific and common names, numbers and sizes of organisms (in ascending order of abundance) caught during the experiment. Sizes were carapace length in mm for school prawns and total length in cm for fish. Na means that these species were not measured. ^economically important in other fisheries (all other species are economically unimportant).

Scientific name	Common name	Numbers	Size range
Metapenaeus macleayi	School prawn^	21 393	4.0–25.0
Herklotsichthys castelnaui	Southern herring	204	5.5–15.0
Uroteuthis sp.	Squid^	94	Na
Siphamia roseigaster	Pink-breasted siphonfish	85	2.5–5.5
Gerres subfasciatus	Silver biddy^	80	4.0–16.0
Pomatomus saltatrix	Tailor^	43	12.0–19.0
Acanthopagrus australis	Yellowfin bream^	40	8.0–23.0
Ambassis marianus	Ramsey's perchlet	24	7.0–9.5
Tetractenos glaber	Toadfish	23	9.0–14.0
Engraulis australis	Australian anchovy^	17	4.0–9.0
Hyperlophus vittatus	Whitebait^	13	3.0–5.5
Neoarius graeffei	Fork-tail catfish	8	9.5–11.0
Pseudorhombus arsius	Largetooth flounder^	5	9.0–18.0
Muraenesox bagio	Common pike eel	3	Na
Dasyatis sp.	Stingray	3	Na
Terapon jarbua	Saddleback grunter	2	9.5–12.0
Pelates sexlineatus	Six-lined trumpeter	2	8.0–15.0
Platycephalus fuscus	Dusky flathead^	1	Na
Scomberoides tol	Needleskin queenfish^	1	Na

TABLE 2 Summaries of Wald *F* statistics from linear mixed models (LMM) assessing the importance of the fixed effect of headline height (conventional: 73 cm, medium: 48 cm; and low: 38 cm) for explaining variability among technical and biological responses, and predicted means (and SEs where appropriate). All numbers and weights (kg) were log-transformed and analysed as absolute and standardized to ha^{-1} trawled. Random effects included 'trawls', 'sides of the vessel', 'days' and 'deployments within days' for all LMMs, and also 'paired trawl sensors' for those LMMs assessing relevant technical variables.

Technical variables	Wald *F*	Conventional 71 cm	Medium 48 cm	Low 38 cm
Wing-end spread (m)	1.77	4.12 (0.07)	4.18 (0.07)	4.22 (0.07)
Distance trawled (km)	0.96	2.35 (0.05)	2.32 (0.05)	2.32 (0.05)
Area trawled (ha)	0.40	0.96 (0.02)	0.97 (0.02)	0.98 (0.02)
Biological variables				
Wt of school prawns	0.72	1.09	0.99	0.94
Wt school prawns ha^{-1}	0.86	1.13	1.01	0.97
No. of school prawns	0.90	575.34	509.41	483.13
No. of school prawns ha^{-1}	0.90	543.59	456.47	481.31
Wt of total bycatch	10.29***	0.71	0.22	0.15
Wt of total bycatch ha^{-1}	10.29***	0.67	0.21	0.15
No of total bycatch	22.63***	23.69	10.17	8.14
No. of total bycatch ha^{-1}	22.62***	22.39	9.61	7.70
No. of southern herring	28.05***	8.87	1.70	1.68
No. of southern herring ha^{-1}	27.66***	8.40	0.67	0.65
No. of squid	1.05	2.07	2.85	1.99
No. of squid ha^{-1}	1.05	1.95	2.68	1.88
No. of pink breasted siphonfish	2.47	1.87	1.82	3.15
No. of pink breasted siphonfish ha^{-1}	4.84*	1.78	1.24	3.05
No. of silver biddy	3.74*	2.05	1.47	0.96
No. of silver biddy ha^{-1}	3.72*	1.93	1.40	0.91
No. of tailor	16.33***	2.32	0.44	0.36
No. of tailor ha^{-1}	16.26***	2.19	0.42	0.34
No. of yellowfin bream	4.00*	1.49	0.90	0.54
No. of yellowfin bream ha^{-1}	3.99*	1.40	0.85	0.51
No. of toadfish	0.11	0.46	0.57	0.46
No. of toadfish ha^{-1}	0.11	0.43	0.54	0.43

***$p < 0.001$; **$p < 0.01$; *$p < 0.05$

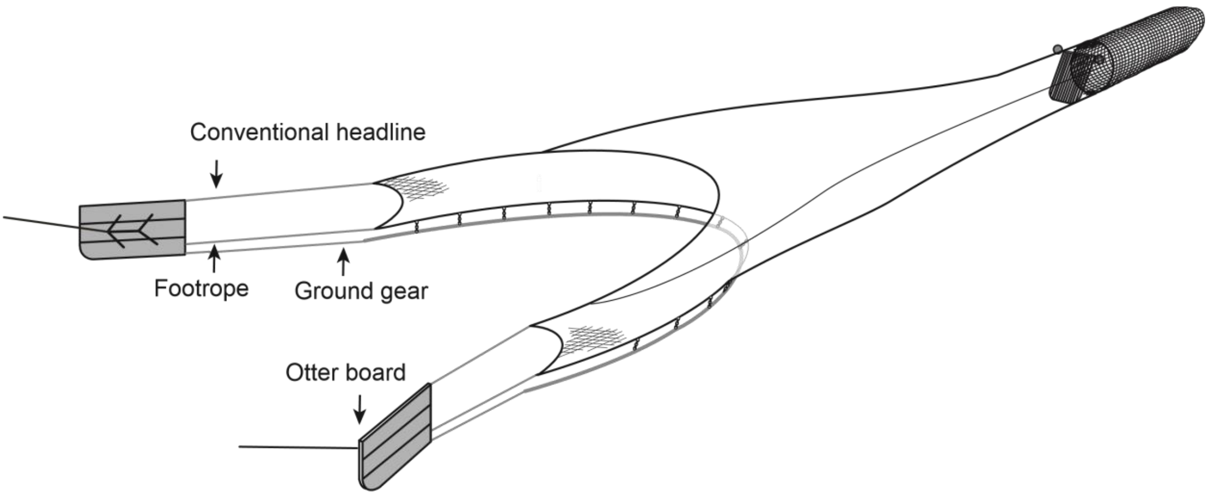
Captions to Figures.

FIGURE 1 Three-dimensional diagrams of the (a) conventional-trawl configuration and (b) locations of the attachment points used at the trailing edge of the otter boards to alter headline height.

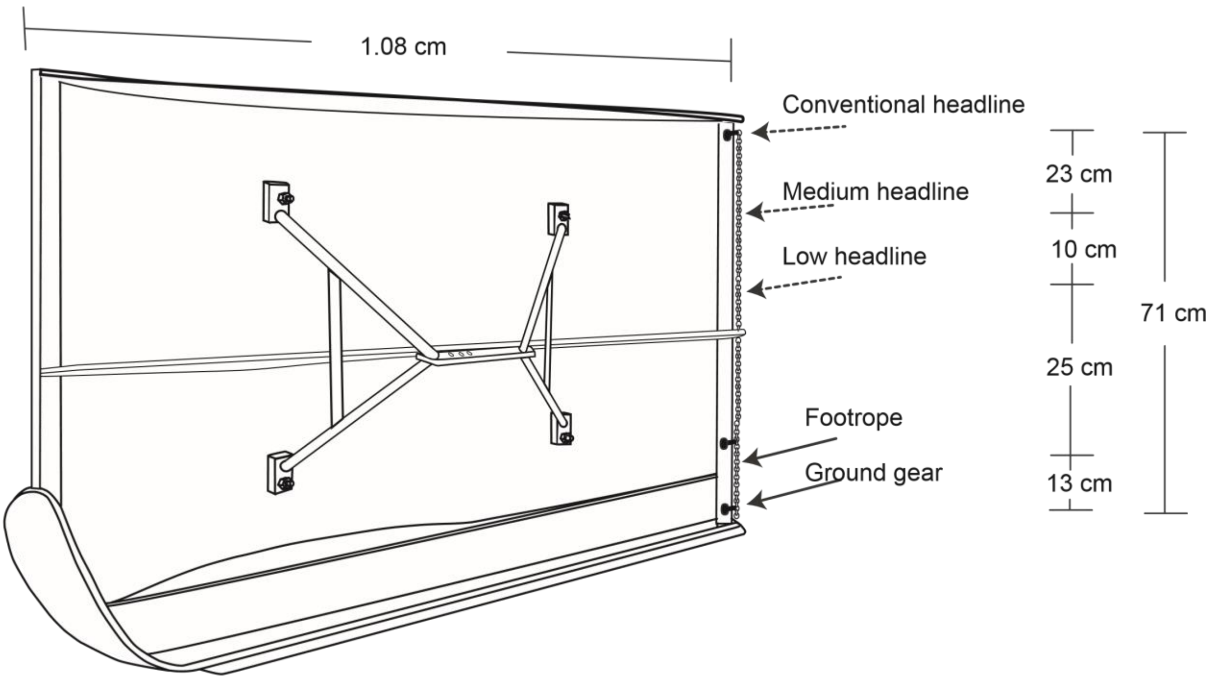
FIGURE 2 Plan of the conventional trawls used in the experiment.

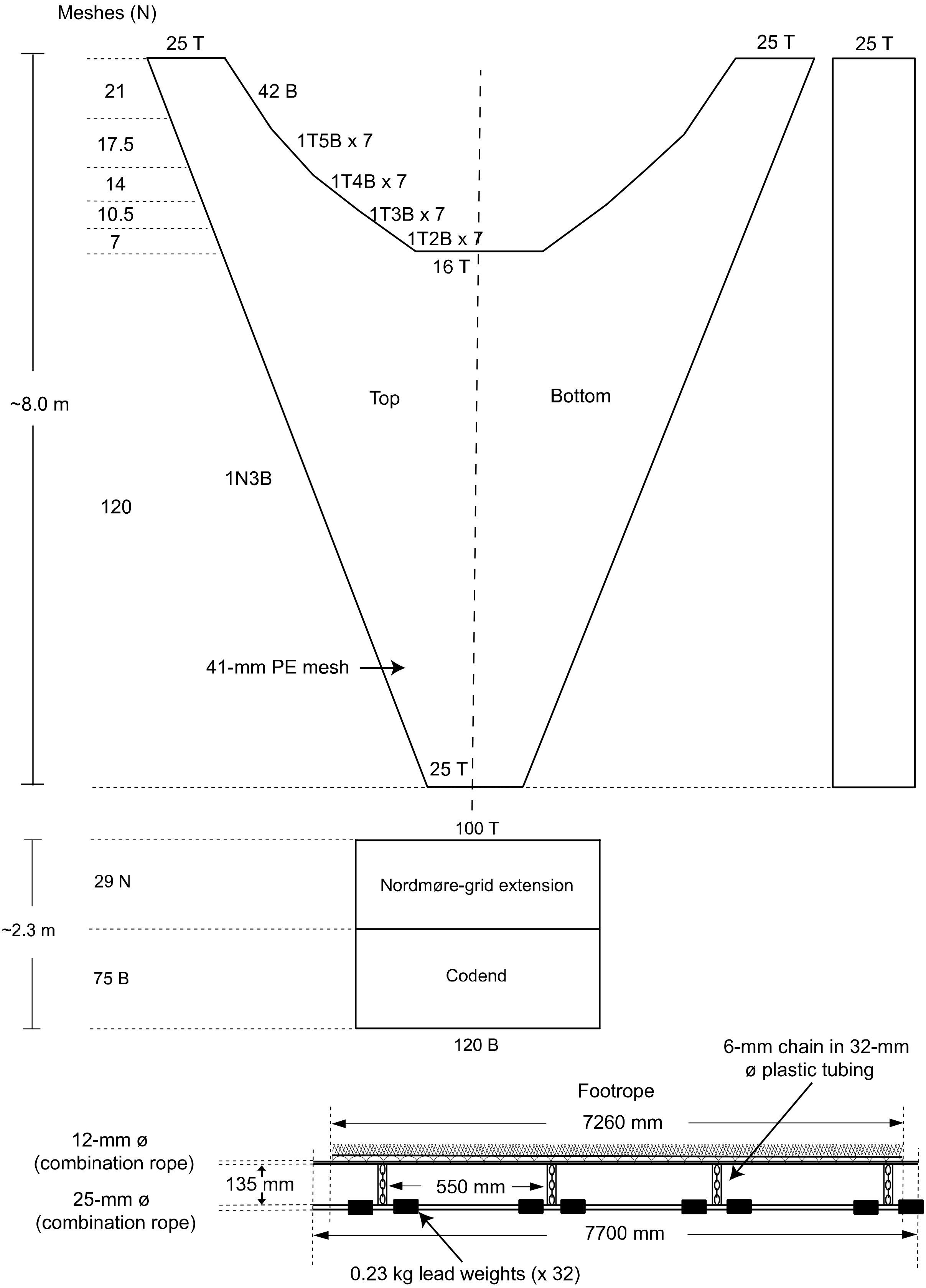
FIGURE 3 Differences in raw (+SE) and predicted mean catches trawled ha $^{-1}$ between trawls configured at the conventional (con; 71 cm) and medium (48 cm) and low (38 cm) headline heights for the weights of (a) school prawns, *Metapenaeus macleayi* and (b) bycatch, and the numbers of (c) southern herring, *Herklotsichthys castelnaui*, (d) squid, *Uroteuthis* sp., (e) pink breasted siphonfish, *Siphamia roseigaster*, (f) silver biddy, *Gerres subfasciatus*, (g) tailor, *Pomatomus saltatrix*, (h) yellowfin bream, *Acanthopagrus australis*, and (i) toadfish, *Tetractenos glaber*. Dissimilar letters above the predicted means indicate significant differences detected in false-discovery-rate pairwise comparisons ($p < 0.05$).

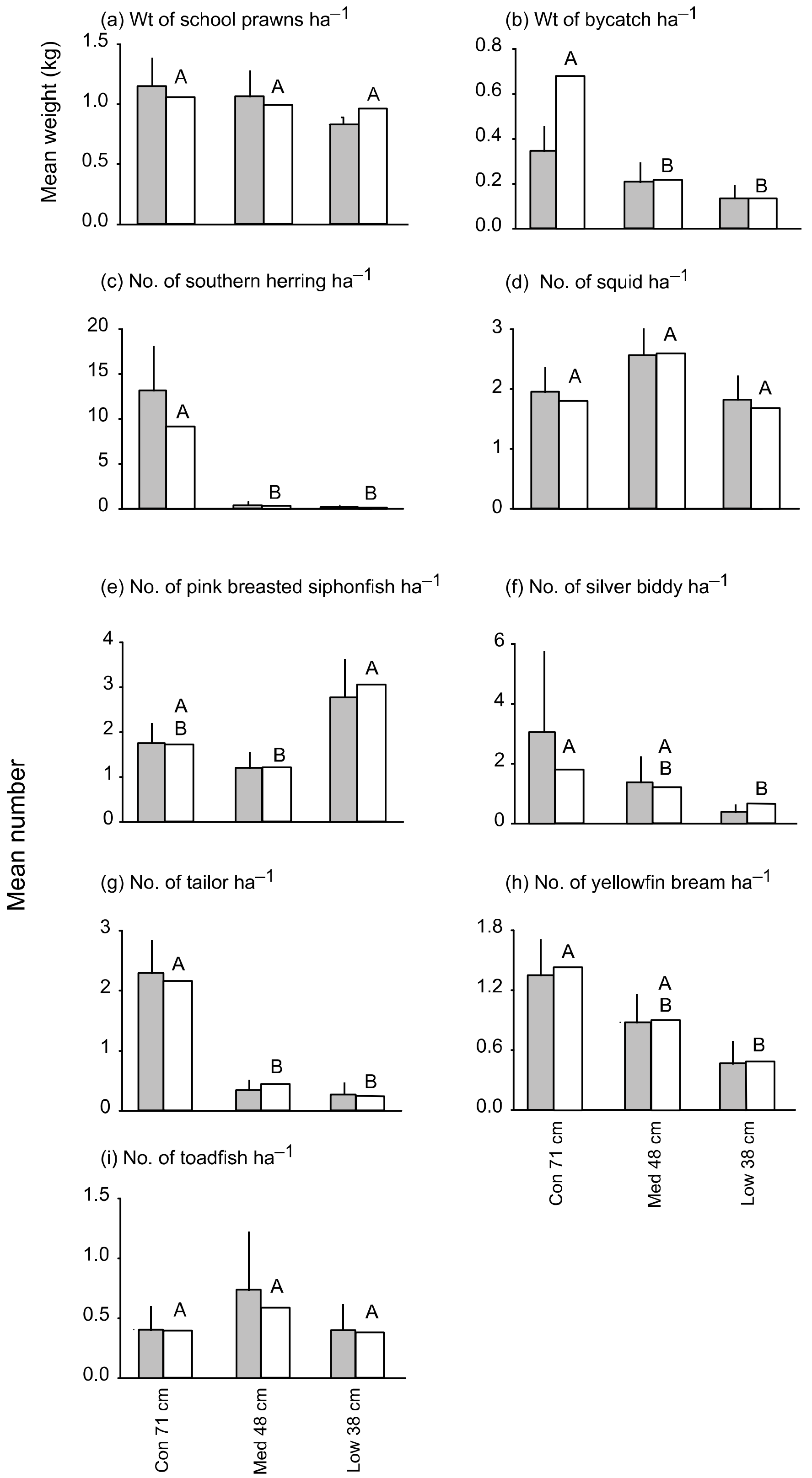
(a) Conventional trawl



(B) Otter board and sweep attachment points




Meshes (N)
25 T
25 T
25 T
21
42 B
17.5
1T5B x 7
14
1T4B x 7
10.5
1T3B x 7
7
1T2B x 7
16 T
~8.0 m
Top
Bottom
1N3B
120
41-mm PE mesh
25 T
100 T
29 N
Nordmøre-grid extension
~2.3 m
75 B
Codend
120 B
6-mm chain in 32-mm
ø plastic tubing
Footrope
7260 mm
12-mm ø
(combination rope)
135 mm
550 mm
25-mm ø
(combination rope)
7700 mm
0.23 kg lead weights (x 32)


(a) Wt of school prawns ha–1
Mean weight (kg)
1.5
1.0
0.5
0.0
A
A
A
(b) Wt of bycatch ha–1
0.8
0.6
0.4
0.2
0.0
A
B
B
(c) No. of southern herring ha–1
20
15
10
5
0
A
B
B
(d) No. of squid ha–1
3
2
1
0
A
A
A
(e) No. of pink breasted siphonfish ha–1
4
3
2
1
0
A
B
B
A
(f) No. of silver biddy ha–1
6
4
2
0
A
A
B
B
Mean number
(g) No. of tailor ha–1
3
2
1
0
A
B
B
(h) No. of yellowfin bream ha–1
1.8
1.2
0.6
0.0
A
A
B
B
Con 71 cm
Med 48 cm
Low 38 cm
(i) No. of toadfish ha–1
1.5
1.0
0.5
0.0
A
A
A
Con 71 cm
Med 48 cm
Low 38 cm