Bycatch Reduction Devices (BRDs) to reduce the incidental catch of cuttlefish in the Spencer Gulf Prawn Fishery

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Executive Summary

The South Australian Spencer Gulf Prawn Fishery is regarded as one of the world's best managed. Operators target western king prawns *Penaeus (Melicertus) latisulcatus*, with nearly all other species discarded. However, two of these bycatch species have evoked significant, although quite different, concerns. Giant cuttlefish *Sepia apama* have undergone a drastic decline in numbers in Spencer Gulf in recent years, with the species listed as 'near threatened' by the International Union for the Conservation of Nature. Whilst there was no correlation between prawn trawling and the decline and it is therefore considered an unlikely contributor, giant cuttlefish are susceptible to trawls during their annual spawning migration through the Gulf and there exists a significant priority to reduce this interaction as much as possible. The other bycatch problem involves large quantities of blue swimmer crabs *Portunus armatus* which currently are separated inside the trawl codend using a large-meshed liner. Due to the additional handling required and the physical damage caused by the crabs' exoskeletons on the relatively soft-bodied prawns and cuttlefish, these crabs would ideally be excluded during towing.

This study examined the utility of mechanical-separating bycatch reduction devices (BRDs) for reducing unwanted bycatches of cuttlefish and crabs. A conventional codend was compared to the smallest and largest practical sizes of Nordmøre-grids (the latter to maximise sorting area), with correspondingly large and low grid angles.

There were reductions by both grids in terms of the numbers and weights of cuttlefish (by 50.4 and 59.7% respectively, for the small grid; and 33.5 and 36.6% respectively, for the large grid), crabs (by 40.2 and 47.5% respectively, for the small grid; and 33.9 and 50.1% respectively, for the large grid) and total bycatch (by 40.9% for the small grid; and 38.1% for the large grid). There was a reduction in the weight of prawns caught by the small grid (of 7.8%) compared to the large grid and control which had identical catches of prawns.

Whilst additional work is required, particularly in regard to the guiding panel, grid bar spacings and escape mortality of the cuttlefish, this study has shown that a modified Nordmøre-grid (in combination with the current very sophisticated management arrangements), could help to substantially reduce bycatch problems associated with

cuttlefish and crabs in this fishery, with minimal commercial impacts on the targeted prawns.

Introduction

Demersal trawls are the main commercial fishing gear used to target prawns, but this method is generally regarded as being among the world's most poorly selective (Alverson et al. 1994). Issues concerning trawl bycatch have attracted significant attention, controversy and priority for decades. Of particular global concern has been the bycatch of endangered species, while the mortality of fishery-specific, charismatic and/or threatened species and other, non-threatened species like juvenile finfish, remains a challenge for local resource management (Hall 1996).

Among the world's prawn-trawl fisheries, the South Australian Spencer Gulf Prawn Fishery is regarded as one of the best managed. It has Marine Stewardship Certification, is a leading example of co-management mixed with sophisticated self-management and is considered a very sustainable and productive fishery. Operators are only permitted to land western king prawns *Penaeus (Melicertus) latisulcatus*, slipper lobsters (bugs) *Ibacus* spp. and southern calamari *Sepioteuthis australis*. The remaining discarded bycatch comprises a diverse assemblage of species; two of which have evoked particular concerns for quite different reasons: (i) giant cuttlefish *Sepia apama* and (ii) blue swimmer crabs *Portunus armatus*.

The giant cuttlefish issue in this fishery recently arose due to a marked decline in the local population; from a peak of ~183,000 spawning animals in 1999 to an estimated 18,530 in 2012 (Steer et al. 2013). This decline led to significant public consternation, media attention and the species being listed by the International Union for Conservation of Nature as 'near threatened' (Barratt and Allcock 2012). While definitive causes for the recent decline remain unknown, mortality from prawn trawling is considered an unlikely contributor because the fishery has been operating for decades during which the giant cuttlefish population remained stable. Nevertheless, giant cuttlefish undertake an annual spawning migration through Spencer Gulf from March to May, during which they are particularly

susceptible to trawls. Complicating this issue is that two other unthreatened cuttlefish species *Sepia novaehollandae* and, to a lesser extent, *Sepia braggi*, are also trawled, but are morphologically identical or similar to *S. apama* and can only be distinguished by lethal internal examination (Dixon, et al. 2014).

The other, longer-standing bycatch problem in this fishery involves large quantities of blue swimmer crabs which are targeted by commercial and recreational trap fishers. Currently, trawled crabs are separated inside trawls using a large-meshed liner (termed a 'crab bag') terminating anterior to the end of the codend. Most prawns, calamari and bugs pass through the crab bag into the codend, whilst larger crabs are retained in it. All crabs caught in the crab bag are then landed on the vessel, quickly sorted and discarded and, because any associated mortality is expected to be low, the crab bag is considered an appropriate strategy for resolving this particular bycatch issue. However, due to (i) the additional handling required and (ii) the physical damage caused by the crabs' exoskeletons on the relatively soft-bodied prawns and calamari, ideally crabs should escape from the trawls during towing.

During the past 30 years, numerous bycatch reduction devices (BRDs) have been developed for prawn-trawl fisheries throughout the world to resolve various bycatch issues (for reviews see Broadhurst 2000, Kennelly 2007). Of particular success have been mechanical-separating BRDs that mostly partition the catch according to size differences (e.g. the 'Nordmøre-grid' described by Isaksen et al. 1992). These BRDs comprise a rigid grid with appropriate bar spacings, typically installed at ~45^{o} in the codend and terminating in an escape exit. The utility of such designs is largely determined by the relative size/morphology (and in some cases behaviour) of the prawns and bycatch species which, in many cases, often overlap - including for those species in the Spencer Gulf Prawn Fishery.

Over the last 20 years, several mechanical-separating BRDs have been tested in Spencer Gulf (mainly to exclude crabs), but none have been implemented. Early work involved trials of various grids and American designs (used to exclude sea turtles in other fisheries) including a 'super-shooter', a 'Seymour grid' and a version of the Nordmøre-grid (McShane 1997). More recent work examined modifications of such designs (Dixon et al. 2014). Whilst some

of these modifications significantly reduced bycatches, unacceptable losses of prawns precluded their implementation.

The purpose of this current study was to identify the boundaries within which the dimensions of a mechanical-separating BRD may exist to reduce the bycatch of cuttlefish and crabs in the Spencer Gulf Prawn Fishery, whilst still maintaining conventional catches of prawns. Note that because the two species of cuttlefish are morphologically identical, any such BRD will need to exclude both. The approach involved comparing what was considered to be the smallest and largest practical grid sizes (the latter to maximise sorting area), and with correspondingly large and low grid angles (to maintain identical codend geometry). The logic underpinning this approach was that, if a large, low-angled grid could not facilitate the escape of cuttlefish whilst maintaining catches of prawns, then mechanical-separating BRDs would not be applicable in this fishery.

Objectives

The objective of this project was to test grid-based bycatch reduction devices (BRDs) to determine the best way forward in developing a BRD for this fishery that excludes cuttlefish and crabs, yet does not reduce prawn catch.

Methods

This study was done during April, 2014 (during the spawning migration of cuttlefish in Spencer Gulf, South Australia (31.42^{o}S 136.75°E) using a double-rigged trawler (the Grozdana B, 22 m and 330 kW – see Fig. 1) fishing in 10 to 30 m across sandy substrata in areas where, based on the skipper's experience, crabs and cuttlefish were likely to be encountered. The trawler had two identical 'Gundry' trawls with 14.63 m headline lengths; each spread by flat-rectangular otter boards (0.9 × 2.7 m) and towed at ~ 1.8 ms^{-1}. Both posterior trawl bodies had zippers attached (Buraschi S145R, 2.0 m long) to facilitate changing extension/codend sections.

Fig. 1 – The Grozdana B that was chartered for the study.

Two extensions and three codends were constructed (Fig. 2A). The extensions were made from identical 41-mm mesh (3.0-mm diameter−Ø braided black twine), measured 150 meshes in the transversal direction (T) and 95 and 110 meshes in the normal direction (N), respectively, and had guiding panels following the specifications provided by Broadhurst et al. (1997) (Fig. 2A). Two Nordmøre-grids were inserted into the posterior extension sections (at the base of the guiding panels), and triangular escape exits were cut (Fig. 2A). Both

Nordmøre-grids were made from solid aluminium rod (20- and 16-mm frame and bars, respectively) with 45-mm bar spaces and measured 1.0 m wide (Figs. 2B and C). The first Nordmøre-grid (termed 'small') was broadly based on those tested in other fisheries, with an aspect ratio of ~1:1.4 (1.40 m long) and was located in the extension at an angle of ~45^o (Broadhurst et al. 1996, 1997, Silva et al. 2011; Fig. 2B) for installation instructions). The second grid (termed 'large') measured 1.98 m long and was positioned at ~30^o from horizontal (Fig. 1C). Both grids were installed so that they had identical fishing heights (i.e. had the same extension/codend diameter) and were rigged with sufficient 200-mm Ø polyurethane floats (behind the upper frame) to achieve neutral buoyancy.

Fig. 2. Schematic representation of (a) a codend and extension with a Nordmøre-grid installed, and the (b) small and (c) large Nordmøre-grids.

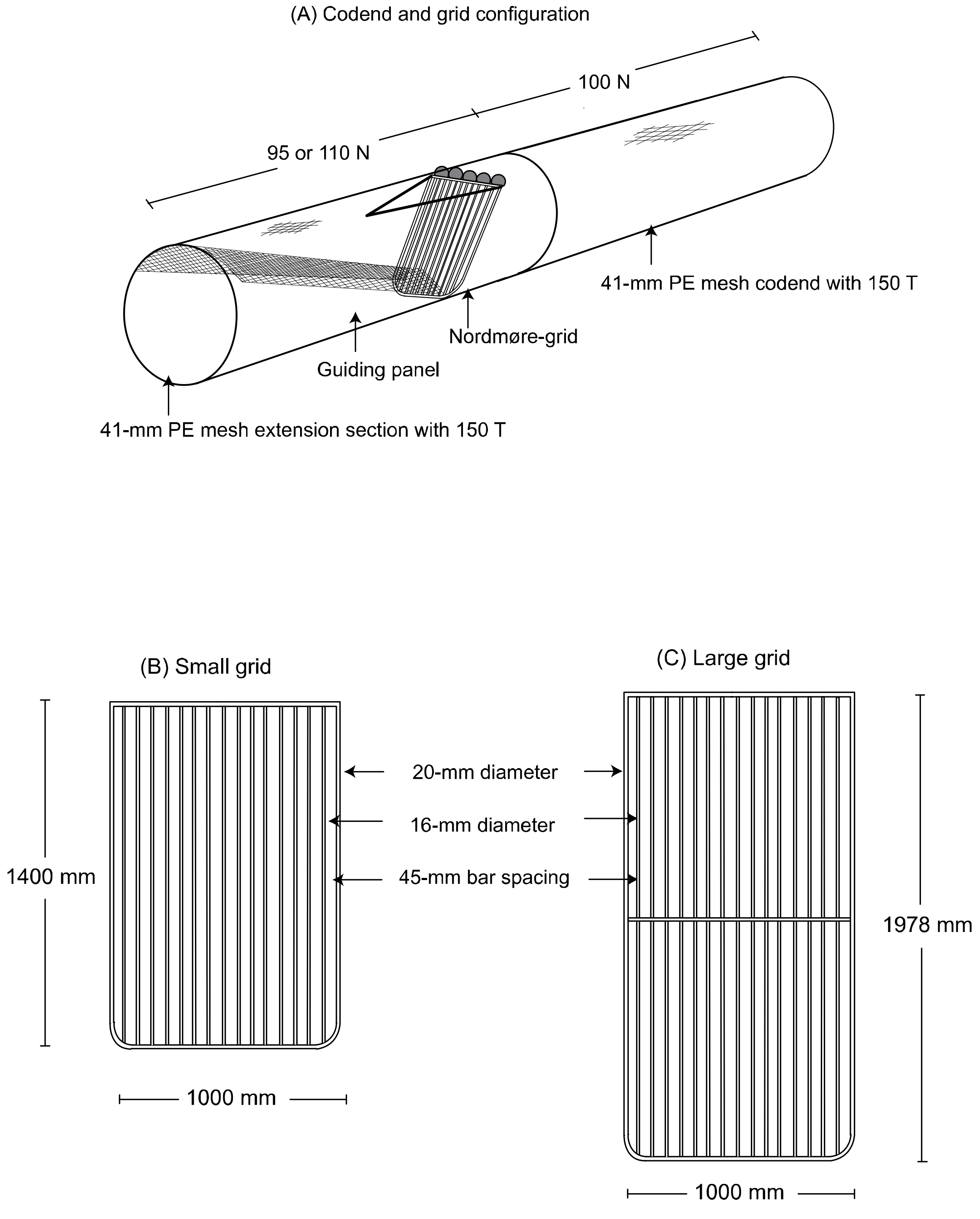


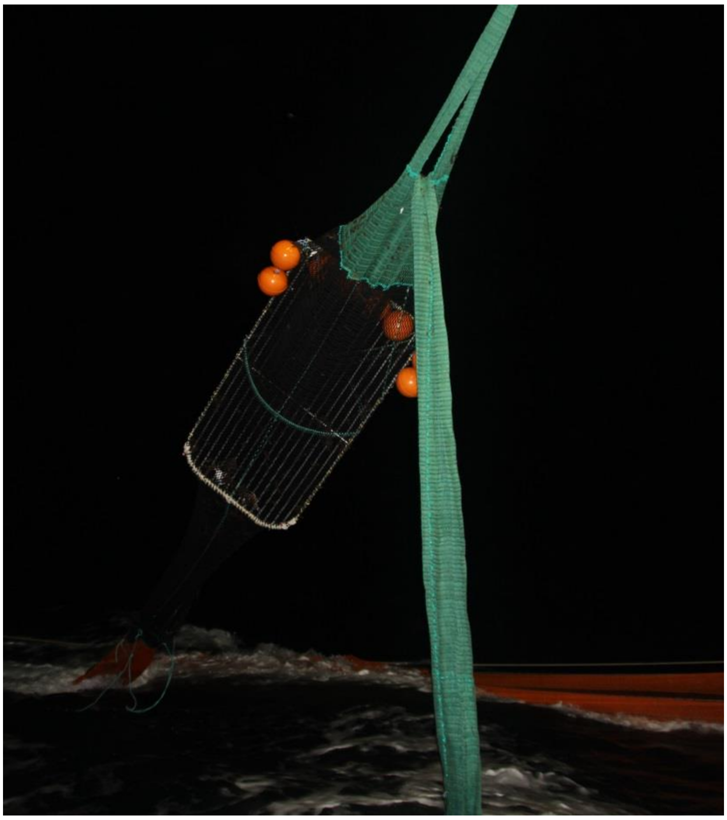
Fig. 3 – The large (left) and small (right) Nordmøre grids in their extensions.

The codends were conventional designs; made from identical 41-mm mesh (2.2-mm Ø braided green twine) and measured 150 T × 100 N. Each codend had a crab bag made from 180-mm braided mesh, measuring 35 T × 35 N inserted into the anterior section. Two of the codends were attached directly posterior to the Nordmøre-grids, while the third was used as a control.

Between 19:00 and 05:30 on three fishing nights, the small and large Nordmøre-grids were tested against the control during simultaneous, paired 30-min deployments (eight and seven, respectively), alternating on each side of the vessel.

Fig. 4 – Getting ready to deploy the large grid.

Fig. 5 – Shooting away the large grid.



At the end of each deployment, data were collected on: the total weights of prawns and various industry size grade sub-categories that included under 8 (‘U8’), under 10 (‘U10’), 11−15, 16−20 and 21−30 individuals per pound, and any damaged or post-moult individuals (termed ‘soft and broken’); the weight of calamari; the weights and numbers of cuttlefish and blue swimmer crabs (representative sub-sampling was required to estimate the numbers of the latter); and the weight of remaining (termed ‘mixed’), and total bycatch. Representative samples of cuttlefish were also collected each night and frozen for later identification of species by SARDI staff.

Data were log-transformed so that the predicted effects would be multiplicative and analysed in linear mixed models (LMMs) that included ‘codend’ as a fixed effect, while ‘sides’, ‘nights’ and the interaction between nights and deployments were included as random terms. The models were fitted using the ASReml package in the *R* statistical language, with the significance of codend determined using a Wald *F* statistic. Any significant effects were subsequently explored using the Benjamini-Hochberg-Yekutieli procedure to control the false discovery rate (FDR) for multiple pair-wise comparisons.

Results

In total, 1801 kg of prawns, 59 kg of retained calamari and 2026 kg of total bycatch were caught during the 15 paired deployments. Cuttlefish (~30−250 mm ML) and blue swimmer crabs (~30−150 mm CW) comprised 5.4 and 64.7% of the total bycatch, respectively and, although not quantified, the remaining mixed subset of bycatch (32.8%) had several small teleosts (most <20 cm total length−TL), including sand trevally *Pseudocaranx wrighti*, red mullet *Upeneichthys porosus*, school whiting *Sillago bassensis*, southern sand flathead *Platycephalus bassensis*, Degen's leather jacket *Thamnaconus degeni* and small-toothed flounder, *Pseudorhombus jenynsii*.

The LMMs detected significant differences among codends for the weights of total prawns and the 10−15 and 21−30 per pound sub-categories, the numbers and weights of cuttlefish and crabs and the weight of total bycatch ($p < 0.05$; Table 1). For prawns, the significant codend effect mostly was explained by a slight reduction in predicted mean weights by the small grid (7.8%) compared to the large grid and control (which had identical catches; FDR, $p < 0.05$; Table 1). The remaining differences in catches reflected significant and comparable reductions by both Nordmøre-grids compared to the control, including the numbers and weights of cuttlefish (by 50.4 and 59.7% respectively, for the small grid; and 33.5 and 36.6% respectively, for the large grid), crabs (by 40.2 and 47.5% respectively, for the small grid; and 33.9 and 50.1% respectively, for the large grid) and total bycatch (by 40.9% for the small grid; and 38.1% for the large grid) (FDR, $p < 0.001$; Table 1). The only variables not affected by codend configuration were calamari and mixed bycatch (i.e. teleosts < ~20 cm TL) (LMM, $p > 0.05$; Table 1).

Table 1. Summaries of Wald *F*-values from linear mixed models assessing the significance of codend (small grid, S; large grid, L; control, C) on key variables, predicted back-transformed (from the log scale) means, and false-discovery-rate (FDR) adjusted paired comparisons of significant differences. Prawn categories are industry counts per pound. −, not relevant; $*p < 0.05$; $**p < 0.01$; $***p < 0.001$

		Predicted means			
Variable	Wald F	Small grid	Large grid	Control	FDR
Wt of prawns					
U8	0.05	3.10	2.9	3.01	−
U10	0.49	3.60	3.46	3.47	−
10−15	4.49*	20.29	21.97	26.73	None detected
16−20	2.43	48.58	53.1	51.86	−
21−30	5.00*	10.23	12.13	11.81	S< L=C
Soft	1.59	6.25	5.55	6.76	−
Total	4.49*	88.64	96.25	96.47	S<C; S=L; and L=C;
Wt of calamari	0.717	2.33	1.65	2.09	−
No. of cuttlefish	18.43***	12.9	17.29	26.01	S=L<C
Wt of cuttlefish	19.08***	2.077	3.27	5.16	S=L<C
No. of crabs	10.81***	467.67	516.43	781.83	S=L<C
Wt of crabs	21.91***	32.82	31.14	62.46	S=L<C
Wt of mixed bycatch	0.08	21.01	21.16	21.93	−
Wt of total bycatch	17.75**	52.28	54.71	88.45	S=L<C

In addition to the above quantitative data, during the experiment information was also gathered concerning the operation of the BRDs. During haulback, some clogging of the guiding panel occurred close to the small grid, but less so for the large grid. This clogging of all species was mainly caused by crabs clinging or being entangled and led to the sub-optimal performance of the BRD because this portion of the catch was unable to be selected along the grid.

The following photographs illustrate some of the features of the catches obtained during the study.

Fig. 6 – A species of *Sepia* caught during the trials. Note that there are three morphologically identical or similar species of cuttlefish caught in this fishery: *Sepia apama, S. novaehollandae* and *S. braggi.* This individual could be any of them.

Fig. 7 – Bycatch from the control codend's crab bag – note the cuttlefish in the foreground.

Fig. 8 – Bycatch from a crab bag from the codend with the small grid installed.

Fig. 9 – Comparisons of catches from the control (left) and large grid (right)

Discussion

In an earlier paper, Broadhurst et al. (2007) described a bycatch reduction framework that involves identifying and then testing the limits within which prospective BRDs should be constructed. Such limits encapsulate known parameters concerning the sizes and behaviours of target and bycatch species and operational factors within the fishery. The current study successfully identified these limits for bycatch issues concerning cuttlefish and crabs in the Spencer Gulf Prawn Fishery.

The results firstly confirmed that, notwithstanding the issues concerning giant cuttlefish and blue swimmer crabs, the Spencer Gulf Prawn Fishery (with a prawn-to-bycatch ratio of ~1:1.16 by weight) is very selective compared to many global prawn-trawl fisheries (Alverson 1994). Nevertheless, as for other trawl fisheries, it is clear that mechanical-separating BRDs, such as the Nordmøre-grid, can reduce bycatch in this fishery, while maintaining prawn catches. The large grid tested here certainly showed this—with 36.6, 50.1 and 38.1% reductions in the weights of cuttlefish, crabs and total bycatch, respectively, with no effect on the catches of prawns.

The small grid yielded adjusted mean reductions in bycatches of cuttlefish, crabs and total bycatch that were greater than those of the large grid – although these differences were not statistically significant. However, the small grid also reduced catches of prawns by 7.8%. The small grid followed those designs previously tested and implemented in several fisheries (e.g. Isaksen et al. 1992, Broadhurst et al. 1996, Brewer et al., 1998; Silva et al. 2011). However, due to (i) the large quantities of blue swimmer crabs caught in Spencer Gulf, (ii) their morphology and sharp exoskeleton, and (iii) propensity to hold meshes with their chelipeds, the original design may have some limitations due to clogging of crabs and associated loss of prawns. By including the very long (4 m) guiding panel at a low seam angle (~26^{o}), it was hypothesised that prawns would fatigue and converge towards the bottom (Watson 1989), while the large numbers of crabs would have sufficient distance to move around blockages (snagged crabs) as they approach the grid.

The above hypothesis was realized in our study, although some crabs were entangled at the base of the small grid, perhaps due to the relatively steep transition in panel-to-grid angle.

The results for the large, shallow-angled grid support this supposition because there was substantially less blockage in this BRD. Increasing the length of the grid also provided considerably more sorting area, which perhaps facilitated the retention of prawns to the same amount as the control.

Despite the success of the large grid, additional work is required to improve its performance, including perhaps slight modifications to the guiding panel to stop finfish and crabs swimming back up to its top edge, and/or smooth canvas sides to further reduce crab entanglement. Another worthwhile modification might be to reduce the bar spacing in the grid; at least until prawn catches are affected, or even potentially beyond this point, if other management tools can be implemented. For example, this study worked within an objective of retaining 100% of prawns, while maximising cuttlefish exclusion. Simply reducing the bar spacing could exclude more cuttlefish (and perhaps some finfish) and, because any escaping prawns should survive, their loss could be compensated with more fishing nights and during times outside the cuttlefish migration (currently the fishery operates as a fleet over ~50-55 nights per year). Clearly, as part of any such work, escape mortalities also need to be estimated for prawns and cuttlefish.

Notwithstanding the need for ongoing work, this study has shown that a modified Nordmøre-grid could go a long way to reducing the bycatch problems associated with giant cuttlefish and blue swimmer crabs in this fishery, with minimal commercial impacts. Combined with the existing management tools used in the fishery (fixed and real-time spatial and temporal closures) and industry-developed technical solutions (the crab bag and on-board sorting systems), such a BRD should significantly contribute to the optimal resource management that is characteristic of this well-managed fishery.

Conclusion

The objective of this project was to test grid-based bycatch reduction devices (BRDs) to determine the best way forward in developing a BRD for this fishery that excludes cuttlefish and crabs, yet does not reduce prawn catch. This objective was clearly achieved in this project.

The results indicated that a Nordmøre-grid modified to be very long and set at a shallow angle should go a long way to reducing the bycatch problems associated with giant cuttlefish and blue swimmer crabs in this fishery, with minimal commercial impacts in terms of prawn catches. Additional work is required to improve the performance of this grid system, including the testing of modifications to the guiding panel to reduce crab entanglement, testing different bar spacings to achieve greater exclusion of cuttlefish and examining the escape mortalities of cuttlefish from the BRD.

Implications

The results from this project have demonstrated that it is quite possible to develop a grid-based BRD for the Spencer Gulf Prawn Fishery that significantly reduces the bycatch of cuttlefish and crabs in the fishery without having any impact on the catches of targeted prawns. The implications of this are quite significant as this fishery and its managers deal with these two bycatch issues in the light of current public attention regarding cuttlefish bycatch and the pending renewal of the fishery's MSC status.

Recommendations

This study has shown that a modified Nordmøre-grid could go a long way to reducing the bycatch problems associated with giant cuttlefish and blue swimmer crabs in this fishery, with minimal commercial impacts on the targeted prawns. However, additional work is required to improve its performance. It is therefore recommended that a second stage of this research should go ahead (as suggested in the original TRF application for this study) that examines:

- Modifications to the guiding panel to stop finfish and crabs swimming back up to its top edge, and/or smooth canvas sides to further reduce crab entanglement.
- Different bar spaces in the grid to identify the optimal spacing that reduces cuttlefish bycatch—at least until prawn catches are affected, or even potentially beyond this point, if other management tools can be implemented to account for any such losses.
- Different grid shapes and angles.
- The escape and discard mortalities of cuttlefish and escape mortality of prawns in the fishery from the developed BRD and conventional gear.

Further Development

Whilst this study clearly demonstrated the potential of a grid-based BRD to reduce the bycatch of cuttlefish and crabs in the Spencer Gulf Prawn Fishery, additional work is required to fine-tune the BRD before its implementation. A second stage of this research should go ahead (as suggested in the original FRDC R&D funding application for this study) that examines:

- Modifications to the guiding panel to stop finfish and crabs swimming back up to its top edge, and/or smooth canvas sides to further reduce crab entanglement.
- Different bar spaces in the grid to identify the optimal spacing that reduces cuttlefish bycatch—at least until prawn catches are affected, or even potentially beyond this point, if other management tools can be implemented to account for any such losses.
- Different grid shapes and angles.
- The escape and discard mortalities of cuttlefish and escape mortality of prawns in the fishery from the developed BRD and conventional gear.

The latter point is particularly important for the cuttlefish bycatch issue in this fishery. As is the case for any bycatch reduction technology in any fishery, it is necessary to show that such technology leads to significant reductions in the mortality of escaping organisms (in this case the soft-bodied cuttlefish) and not just a reduction in capture.

Extension and Adoption

The Spencer Gulf Prawn fishers have been heavily involved in this research. The work was done on one of their vessels, with its nets, crew and skipper. The Executive Officer of the Association is also a Co-Investigator of the project.

During the field work, all data was entered onto computer each night and summary information on each comparison (as arithmetic means and SEs) were presented to the skipper so we could discuss the work and the performance of the gears as we conducted the experiment.

Also, immediately after the last night's work, I prepared a summary report of the field work and the findings and provided it to relevant stakeholders and for distribution to the whole fleet.

The outcome from this pilot TRF project has gone a long way in developing a BRD that will exclude cuttlefish and crabs caught as bycatch in this fishery with minimal loss of prawns. However, more work needs to be done to refine the BRDs developed here. In particular, modifications to the guiding panel and bar spacing could yield greater exclusion of cuttlefish and crabs with minimal prawn loss. Further, work on the survival of escaping cuttlefish should also be done.

Once this follow-up work has been done and a suitable BRD is developed, it may be incorporated into the management arrangements for this fishery quite rapidly and used in places and times where significant cuttlefish interactions occur.

Project materials developed

A preliminary report about this project was prepared the same day as the field work concluded (see Appendix 1). It was done for circulation amongst all interested parties and so that the whole fishing fleet could get the data as soon as possible. The preliminary report did not contain any statistical analyses or modelling work but contained the simple arithmetic means of catches and bycatches. The scientific paper (below) and this present report contains the corrected modelled means and statistical analyses.

A scientific paper (co-authored by Matt Broadhurst) has been prepared for submission to an international journal entitled "Applying a technical paradigm to mitigate the bycatch of giant cuttlefish *Sepia apama* in an Australian penaeid-trawl fishery". It contains most of the information provided in this report and is provided at Appendix 2.

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Appendix 1

Spencer Gulf Prawn Trawl Bycatch Reduction Trial

Brief Preliminary Report

This brief report summarizes the three nights of trawling we completed earlier today (25 April, 2014) onboard the Grozdana B in Spencer Gulf testing two designs of bycatch reduction grids. It is prepared to give the fleet as much information as possible, as soon as possible.

We originally had planned to fish for four nights, but had to miss the first night due to weather. We therefore started on the night of 22 April.

We began by running two conventional codends against each other to identify any differences between the nets/sides. Preliminary examination of the data confirmed reasonably similar performance.

We then tested specially-designed bycatch reduction grids (one small and set at 45 degrees, and one large and set at 30 degrees) against a control (a conventional codend), swapping them from side-to-side throughout the three nights and collecting data on prawn catches, total bycatch weights, weights and numbers of crabs and cuttlefish and weights of squid. Subsampling and extrapolation was required to estimate the total weights and numbers of crabs. We also collected samples of cuttlefish (each night) that were frozen and will be examined for subsequent identification and measurement by SARDI.

We completed four paired comparisons on night 1, seven on night 2 and four on night 3. These comparisons were eight trials of the small grid and seven of the large grid; always against the control. Three other trials were abandoned due to twisting of the small grid (twice) and blown nets (once – the last trial). The large grid never twisted and performed quite well on all occasions in terms of lifting, etc.

Each night we entered the data onto our computer so that we could discuss the results with the skipper and determine how to proceed.

A (very) preliminary summary of the data is in the table below (and may contain errors as we have not had a chance to double-check everything - we only just got off the boat today). But the data, whilst showing that there is no “silver bullet” for eliminating the bycatch of cuttlefish, does show some promising results in how bycatch (especially that of crabs) could be reduced in this fishery. The full report will provide complete statistical analyses of the information and recommendations on potential future steps.

A special thanks to Clint Scharfe and crew of the Grozdana B (Max Sturman, Bob Lovett and David Verran) whose professionalism and friendliness made the trip a very successful and enjoyable experience.

Preliminary Results					
Average % reductions using the two grids (-ve means an increase)					
Std errors are estimates of the variation around the averages					
	SMALL GRID			LARGE GRID	
	average	std error		average	std error
TOTAL PRAWNS	8.0	3.2		-0.2	3.8
Cuttlefish (no.)	46.0	7.5		28.5	5.5
Cuttlefish (wt.)	56.8	6.3		33.6	9.8
Crabs (no.)	35.2	10.3		27.1	7.8
Crabs (wt.)	47.3	6.4		42.3	8.1
TOTAL BYCATCH (wt.)	41.7	6.3		31.2	5.9

Appendix 2

Applying a technical paradigm to mitigate the bycatch of giant cuttlefish *Sepia apama* in an Australian penaeid-trawl fishery

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ABSTRACT: The South Australian Spencer Gulf Prawn Fishery is regarded as one of the world's best managed. Operators target western king prawns *Melicertus latisulcatus*, with nearly all other species discarded; two of which have evoked significant, although quite different, concerns. Giant cuttlefish *Sepia apama* have undergone a drastic decline in numbers in Spencer Gulf in recent years, with the species listed as 'near threatened' by the International Union for the Conservation of Nature. Whilst penaeid trawling is considered an unlikely contributor to this decline, *Sepia* spp. are susceptible to trawls during their annual spawning migration. The other bycatch problem involves large quantities of *Portunus armatus* which currently are separated inside the trawl using a large-meshed liner. Due to the additional handling required and the physical damage caused by the crabs' exoskeletons on the soft-bodied *M. latisulcatus* and *Sepia* spp., *P. armatus* would ideally escape during towing. This study examined the utility of mechanical-separating bycatch reduction devices (BRDs) for reducing unwanted bycatches of *Sepia* spp. and *P. armatus*. We compared (against conventional codends) the smallest and largest practical sizes of Nordmøre-grids (the latter to maximise sorting area), with correspondingly large and low grid angles. The large Nordmøre-grid significantly reduced *Sepia* spp., *P. armatus* and total bycatch (by 33 to 50%), but had no effect on catches of *M. latisulcatus*. Whilst additional work is required, a modified Nordmøre-grid should help to resolve the bycatch problems associated with *P. armatus* and *S. apama* in this fishery, with minimal commercial impacts.

INTRODUCTION

Demersal trawls are the main commercial fishing gear used to target penaeids, however this method is generally regarded as being among the world's most poorly selective (Alverson et al. 1994). Issues concerning trawl bycatch have attracted significant attention, controversy and priority for decades. Of particular global concern has been the bycatch of endangered species like sea turtles, while the mortality of fishery-specific, charismatic and/or threatened species remains a challenge for local resource management (Hall 1996).

Among the world's penaeid-trawl fisheries, the South Australian Spencer Gulf Prawn Fishery is regarded as one of the best managed. It has Marine Stewardship Certification, is a leading example of co-management mixed with sophisticated self-management and is considered a very sustainable, profitable and productive fishery. Operators are only permitted to land western king prawns *Melicertus latisulcatus*, slipper lobsters *Ibacus* spp. and southern calamari *Sepioteuthis australis*. The remaining discarded bycatch comprises a diverse assemblage of species; two of which have evoked particular concerns for quite different reasons: (i) giant cuttlefish *Sepia apama* and (ii) blue swimmer crabs *Portunus armatus*.

The *Sepia apama* issue in this fishery recently arose due to a marked decline in the local population; from a peak of ~183,000 spawning animals in 1999 to an estimated 18,530 in 2012 (Steer et al. 2013). This decline led to significant public consternation, media attention and the species being listed by the International Union for Conservation of Nature as 'near threatened' (Barratt and Allcock 2012). While definitive causes for the recent decline remain unknown, mortality from penaeid trawling is considered an unlikely contributor because the fishery has been operating for decades during which the *S. apama* population remained stable. Nevertheless, *S. apama* (at 30−250

mm mantle length−ML) undertake an annual spawning migration through Spencer Gulf from March to May, during which they are particularly susceptible to trawls. Complicating this issue is that two other species of unthreatened cuttlefish *S. novaehollandae* and *S. braggi* are also trawled, but are morphologically similar to *S. apama* and can only be distinguished by lethal internal examination (Dixon, et al. 2014).

The other, longer-standing bycatch problem involves large quantities of *Portunus armatus* (30−150 mm carapace width−CW) which are targeted by commercial and recreational trap fishers. Currently, trawled *P. armatus* are separated inside trawls using a large-meshed liner (termed a 'crab bag') terminating anterior to the end of the codend. Most *Melicertus latisulcatus*, *Sepioteuthis australis* and *Ibacus* spp. pass through the crab bag into the codend, whilst larger *P. armatus* are retained in it. All *P. armatus* caught in the crab bag are then landed on the vessel, quickly sorted and discarded and, because any associated mortality is expected to be low, the crab bag is considered an appropriate strategy for resolving this particular bycatch issue. However, due to (i) the additional handling required and (ii) the physical damage caused by the crabs' exoskeletons on the soft-bodied *M. latisulcatus, S. australis* and *Sepia* spp., ideally *P. armatus* would escape from the trawls during towing.

During the past 30 years, numerous bycatch reduction devices (BRDs) have been developed for penaeid-trawl fisheries throughout the world to resolve various selectivity issues (for reviews see Broadhurst 2000, Kennelly 2007). Of particular success have been mechanical-separating BRDs that mostly partition the catch according to size differences (e.g. the 'Nordmøre-grid' described by Isaksen et al. 1992). These BRDs comprise a rigid grid with appropriate bar spacings, typically installed at ~45^{o} in the codend and terminating in an escape exit. The utility of such designs is largely

determined by the relative size/morphology (and in some cases behaviour) of the penaeids and bycatch species which, in many cases, often overlap—including for those species in the Spencer Gulf fishery.

Over the last 20 years, several mechanical-separating BRDs have been tested in Spencer Gulf (mainly to exclude *Portunus armatus*), but none have been implemented. Early work involved trials of various grids and American designs (used to exclude sea turtles in other fisheries) including a 'super-shooter', a 'Seymour grid' and a version of the Nordmøre-grid (McShane 1997). More recent work examined modifications of such designs (Dixon et al. 2014). Whilst some of these modifications significantly reduced bycatches, they did so inconsistently and unacceptable losses of *M. latisulcatus* precluded their implementation.

The purpose of this current study was to identify the boundaries within which the dimensions of a mechanical-separating BRD may exist to reduce the bycatch of *Sepia* spp. and *Portunus armatus* in the Spencer Gulf fishery, whilst still maintaining conventional catches of *Melicertus latisulcatus*. Note that because *Sepia apama*, *S. novaehollandae* and *S. braggi* are morphologically similar, any such BRD will need to exclude both. Our approach involved comparing what was considered to be the smallest and largest practical grid sizes (the latter to maximise sorting area), and with correspondingly large and low grid angles (to maintain identical codend geometry). The logic underpinning this approach was that, if a large, low-angled grid could not facilitate the escape of *Sepia* spp. and *P. armatus* whilst maintaining catches of *M. latisulcatus*, then mechanical-separating BRDs would not be applicable in this fishery.

MATERIALS AND METHODS

This study was done during April, 2014 (during the *Sepia spp.* migration) in Spencer Gulf, South Australia (31.42°S 136.75°E) using a double-rigged trawler (22 m and 330 kW) fishing in 10 to 30 m across sandy substrata in areas where, based on the skipper's experience, *Sepia* spp. and *Portunus armatus* were likely to be encountered. The trawler had two identical 'Gundry' trawls with 14.63 m headline lengths; each spread by flat-rectangular otter boards (0.9 × 2.7 m) and towed at ~ 1.8 ms^{-1}. Both posterior trawl bodies had zippers attached (Buraschi S146R, 2.0 m long) to facilitate changing extension/codend sections.

Two extensions and three codends were constructed (Fig. 1A). The extensions were made from identical 41-mm mesh (3.0-mm diameter−Ø braided black twine), measured 150 meshes in the transversal direction (T) and 95 and 110 meshes in the normal direction (N), respectively, and had guiding panels following the specifications provided by Broadhurst et al. (1997) (Fig. 1A). Two Nordmøre-grids were inserted into the posterior extension sections (at the base of the guiding panels), and triangular escape exits were cut (Fig. 1A). Both Nordmøre-grids were made from solid aluminium rod (20- and 16-mm frame and bars, respectively) with 45-mm bar spaces and measured 1.0 m wide (Figs. 1B and C). The first Nordmøre-grid (termed 'small') was broadly based on those tested in other fisheries, with an aspect ratio of ~1:1.4 (1.40 m long) and was located in the extension at an angle of ~45° (Broadhurst et al. 1996, 1997, Silva et al. 2011; Fig. 1B) for installation instructions). The second grid (termed large) measured 1.98 m long and was positioned at ~30° (Fig. 1C). Both grids were installed so that they had identical fishing heights (i.e. had the same extension/codend diameter) and were rigged with sufficient 200-mm Ø polyurethane floats (behind the upper frame) to achieve neutral buoyancy.

The codends were conventional designs; made from identical 41-mm mesh (2.2-mm Ø braided green twine) and measured 150 T × 100 N. Each codend had a crab bag made from 180-mm braided mesh, measuring 35 T × 35 N inserted into the anterior section. Two of the codends were attached directly posterior to the Nordmøre-grids, while the third was used as a control.

Between 19:00 and 05:30 on three fishing nights, the small and large Nordmøre-grids were tested against the control during simultaneous, paired 30-min deployments (eight and seven, respectively), alternating on each side of the vessel. At the end of each deployment, data were collected on: the total weights of *Melicertus latisulcatus* and various industry size grades that included under 8, under 10, 11−15, 16−20 and 21−30 individuals per pound, and any damaged or post-moult individuals (termed 'soft'); the weight of *Sepioteuthis australis*; the weights and numbers of *Sepia* spp. and *Portunus armatus* (representative sub-sampling was required to estimate the numbers of the latter); and the weight of remaining (termed 'mixed'), and total bycatch.

Data were log-transformed so that the predicted effects would be multiplicative and analysed in linear mixed models (LMMs) that included 'codend' as a fixed effect, while 'sides', 'nights' and the interaction between nights and deployments were included as random terms. The models were fitted using the ASReml package in the *R* statistical language, with the significance of codend determined using a Wald *F* statistic. Any significant effects were subsequently explored using the Benjamini-Hochberg-Yekutieli procedure to control the false discovery rate (FDR) for multiple pair-wise comparisons.

RESULTS

A total of 1801, 59 and 2026 kg of *Melicertus latisulcatus*, retained *Sepioteuthis australis* and total bycatch, respectively, were caught during the 15 paired deployments. *Sepia* spp. (~30−250 mm ML) and *Portunus armatus* (~30−150 mm CW) comprised 5.4 and 64.7% of the total bycatch, respectively and, although not quantified, the remaining mixed subset of bycatch (32.8%) had several small teleosts (most <20 cm total length−TL), including sand trevally *Pseudocaranx wrighti*, red mullet *Upeneichthys porosus*, school whiting *Sillago bassensis*, southern sand flathead *Platycephalus bassensis*, Degen's leather jacket *Thamnaconus degeni* and small-toothed flounder, *Pseudorhombus jenynsii*.

The LMMs detected significant differences among codends for the weights of total *Melicertus latisulcatus* and the 10−15 and 21−30 per pound sub-categories, the numbers and weights of *Sepia spp.* and *Portunus armatus* and the weight of total bycatch (p < 0.05; Table 1). For *M. latisulcatus*, the significant codend effect mostly was explained by a slight reduction in predicted mean weights by the small grid (7.8%) compared to the large grid and control (which had identical catches; FDR, p < 0.05; Table 1). The remaining differences in catches reflected significant and comparable reductions by both Nordmøre-grids compared to the control, including the numbers and weights of *Sepia* spp. (by 50.4 and 59.7% respectively, for the small grid; and 33.5 and 36.6% respectively, for the large grid), *P. armatus* (by 40.2 and 47.5% respectively, for the small grid; and 33.9 and 50.1% respectively, for the large grid) and total bycatch (by 40.9% for the small grid; and 38.1% for the large grid) (FDR, p < 0.001; Table 1). The only variables not affected by codend configuration were *Sepioteuthis australis* and mixed bycatch (i.e. teleosts < ~20 cm TL) (LMM, p > 0.05; Table 1).

In addition to the above quantitative data, during the experiment we also gathered information concerning the operation of the BRDs. During haulback, we noticed some clogging of the guiding panel close to the small grid, but less so for the large grid. This clogging of all species was mainly caused by *Portunus armatus* clinging or being entangled, and was included in the catch sampled for each replicate.

DISCUSSION

In an earlier paper (Broadhurst et al. 2007), we described a bycatch reduction framework that involves identifying and then testing the limits within which prospective BRDs should be constructed. Such limits encapsulate known parameters concerning the sizes and behaviours of target and bycatch species and operational factors within the fishery. The current study successfully identified these limits for bycatch issues concerning *Sepia* spp. and *Portunus armatus* in the Spencer Gulf Prawn Fishery.

The results firstly confirmed that, notwithstanding the issues concerning *Sepia apama* and *Portunus armatus*, the Spencer Gulf fishery (with a prawn-to-bycatch ratio of ~1:1.16 by weight) is very selective compared to many global penaeid-trawl fisheries (Alverson 1994). Nevertheless, as for other trawl fisheries, it is clear that mechanical-separating BRDs, such as the Nordmøre-grid, can reduce bycatch in this fishery, while maintaining penaeid catches. The large grid tested here certainly showed this—with 36.6, 50.1 and 38.1% reductions in the weights of *Sepia* spp., *Portunus armatus* and total bycatch, respectively, with no effect on the catches of *Melicertus latisulcatus*.

The small grid yielded predicted mean reductions in bycatches of *Sepia* spp., *Portunus armatus* and total bycatch that were greater than those of the large grid – although these differences were not statistically significant. However, the small grid also reduced catches of *Melicertus latisulcatus* by 7.8%. The small grid followed those designs previously tested and implemented in several fisheries (e.g. Isaksen et al. 1992, Broadhurst et al. 1996, Brewer et al., 1998; Silva et al. 2011). However, we recognised that (i) due to the large quantities of *Portunus armatus* caught in Spencer Gulf, (ii) their morphology and sharp exoskeletons, and (iii) propensity to hold meshes with their chelipeds, the original design may have some limitations due to clogging of *P. armatus* and associated loss of *Melicertus latisulcatus*. By including the very long (4 m) guiding panel at a low seam angle (~26^{o}), we hypothesised that *M. latisulcatus* would fatigue and orientate towards the bottom (Watson 1989), while the large numbers of *Portunus armatus* would have sufficient distance to be separated out as they approached the grid.

The above hypothesis was realized in our study, although some *P. armatus* were entangled at the base of the small grid, perhaps due to the relatively steep transition in panel-to-grid angle. The results for the large, shallow-angled grid support this supposition because there was substantially less blockage in this BRD. Increasing the length of the grid also provided considerably more sorting area, which perhaps facilitated the retention of *Melicertus latisulcatus* to the same amount as the control.

Despite the success of the large grid, additional work is required to improve its performance, including perhaps slight modifications to the guiding panel to stop teleosts and *Portunus armatus* swimming back up to its top edge, and/or smooth canvas sides to further reduce *P. armatus* entanglement. Another worthwhile modification might be to reduce the bar spacing in the grid; at

least until *Melicertus latisulcatus* catches are affected, or even potentially beyond this point, if other management tools can be implemented. For example, we worked within an objective of retaining 100% of *M. latisulcatus*, while maximising *Sepia* spp. exclusion. Simply reducing the bar spacing could exclude more *Sepia* spp. (and perhaps some teleosts) and, because any escaping *M. latisulcatus* should survive, their loss could be compensated with more fishing nights during times outside the *Sepia apama* migration (currently the fishery operates as a fleet over ~ 50-55 nights per year). Clearly, as part of any such work, escape mortalities also need to be estimated for *M. latisulcatus* and *Sepia* spp*.*

Notwithstanding the need for ongoing work, this study has shown that a modified Nordmøre-grid could go a long way to resolving the bycatch problems associated with *Sepia apama* and *Portunus armatus* in this fishery, with minimal commercial impacts. Combined with the existing management tools used in the fishery (fixed and real-time spatial and temporal closures) and industry-developed technical solutions (the crab bag and on-board sorting systems), such a BRD should significantly contribute to the optimal resource management that is characteristic of this well-managed fishery.

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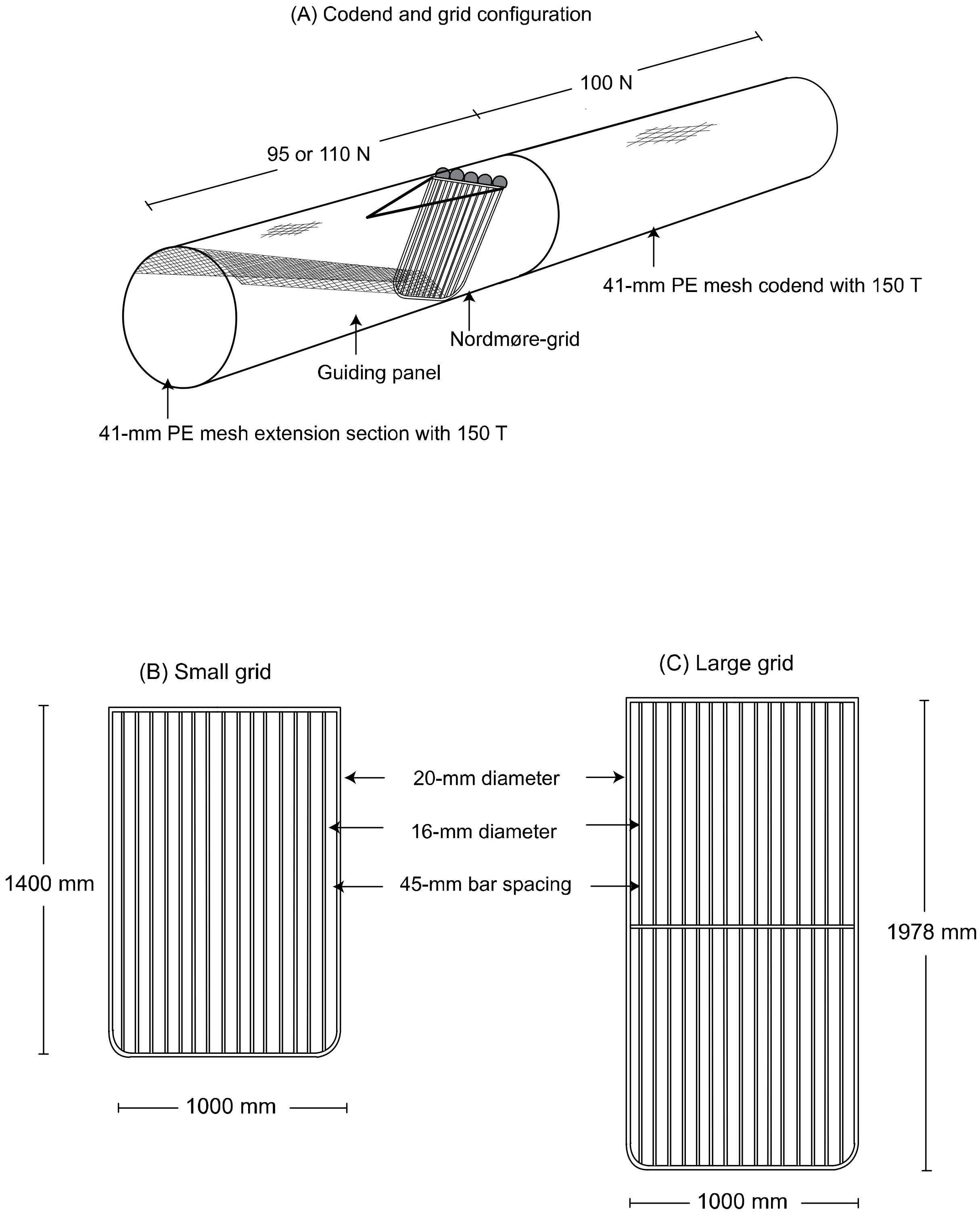
Table 1. Summaries of Wald *F*-values from linear mixed models assessing the significance of codend (small grid, S; large grid, L; control, C) on key variables, predicted back-transformed (from the log scale) means, and false-discovery-rate (FDR) adjusted paired comparisons of significant differences. *Melicertus latisulcatus* categories are industry counts per pound. −, not relevant; *$p < 0.05$; **$p < 0.01$; ***$p < 0.001$

		Predicted means			
Variable	Wald F	Small grid	Large grid	Control	FDR
Wt of *Melicertus latisulcatus*					
U8	0.05	3.10	2.9	3.01	−
U10	0.49	3.60	3.46	3.47	−
10−15	4.49*	20.29	21.97	26.73	None detected
16−20	2.43	48.58	53.1	51.86	−
21−30	5.00*	10.23	12.13	11.81	S< L=C
Soft	1.59	6.25	5.55	6.76	−
Total	4.49*	88.64	96.25	96.47	S<C; S=L; and L=C;
Wt of *Sepioteuthis australis*	0.717	2.33	1.65	2.09	−
No. of *Sepia* spp.	18.43***	12.9	17.29	26.01	S=L<C
Wt of *Sepia* spp.	19.08***	2.077	3.27	5.16	S=L<C
No. of *Portunus armatus*	10.81***	467.67	516.43	781.83	S=L<C
Wt of *Portunus armatus*	21.91***	32.82	31.14	62.46	S=L<C
Wt of mixed bycatch	0.08	21.01	21.16	21.93	−
Wt of total bycatch	17.75**	52.28	54.71	88.45	S=L<C

Figure caption

Fig. 1. Schematic representation of (a) a codend and extension with a Nordmøre-grid installed, and the (b) small and (c) large Nordmøre-grids.


(A) Codend and grid configuration
100 N
95 or 110 N
41-mm PE mesh codend with 150 T
Nordmøre-grid
Guiding panel
41-mm PE mesh extension section with 150 T
(B) Small grid
(C) Large grid
20-mm diameter
16-mm diameter
45-mm bar spacing
1400 mm
1000 mm
1978 mm
1000 mm