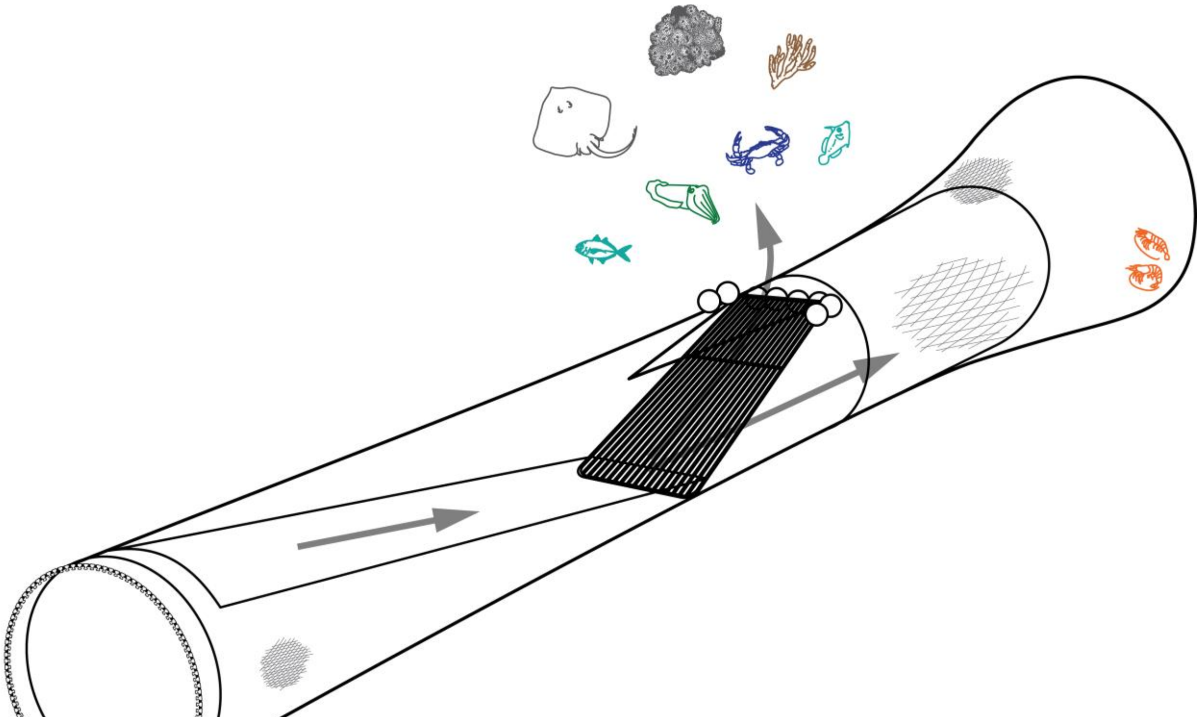
Refining a Nordmøre-grid to minimise the incidental catch of cuttlefish and crabs in the Spencer Gulf Prawn Fishery



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October 2017

FRDC Project No. 2015/019

ISBN: 978-1-876007-01-0

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2015/019

2017

This publication (and any information sourced from it) should be attributed to Noell, C.J., Broadhurst, M.K. and Kennelly, S.K. South Australian Research and Development Institute (Aquatic Sciences) 2017. *Refining a Nordmøre-grid to minimise the incidental catch of cuttlefish and crabs in the Spencer Gulf Prawn Fishery*. Adelaide, October.

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In submitting this report, the researcher has agreed to FRDC publishing this material in its edited form.

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Acknowledgments

This project was supported by funding from the Fisheries Research and Development Corporation (Project No. 2015/019). We acknowledge the skill, professionalism and enthusiasm of the skipper (Ashley Lukin) and crew (Geoff Earle, Tom Clarke and Josh Redden) of the 'Lunar Sea' for ensuring the fieldwork was successful. Thanks are extended to Geoff Johnson and Steve Everson for skilfully fabricating the BRDs, Owen Burnell, Graham Hooper, Matt Heard and Stuart Sexton for fieldwork support, and Dave Craig for making several codends. We also thank Annabel Jones, Brad Milic, Steve Shanks, Simon Clark and the Management Committee of the Spencer Gulf and West Coast Prawn Fishermen's Association for their support. Stephen Mayfield, Simon Clark and Steve Shanks provided helpful comments that improved the manuscript.

Abbreviations

AB	all-bar taper
B	bars (of mesh)
BRD	bycatch reduction device
FDR	false-discovery rate
LMM	linear mixed model
MSC	Marine Stewardship Council
N	normals – number of meshes or cuts in the normal direction
PE	polyethylene
PIRSA	Primary Industries and Regions South Australia
SARDI	South Australian Research and Development Institute
SGPF	Spencer Gulf Prawn Fishery
SGWCPFA	Spencer Gulf and West Coast Prawn Fishermen's Association
SMO	stretched-mesh opening
T	transversals – number of meshes or cuts in the transverse direction
TL	total length
U10	under (or less than) 10 prawns per pound
U8	under (or less than) 8 prawns per pound
1N1B	1-normal 1-bar taper
1N2B	1-normal 2-bar taper
10–15	10–15 prawns per pound
16–20	16–20 prawns per pound
21–30	21–30 prawns per pound

Executive summary

What the report is about

This report presents the findings of bycatch reduction device (BRD) trials undertaken for the Spencer Gulf Prawn Fishery (SGPF) in South Australia using a 'Nordmøre-grid'—a type of BRD that mechanically separates organisms based on size and/or morphological differences. Combined with previous work by the Co-Investigators, who identified the parameters required for the successful implementation of a Nordmøre-grid in this fishery, this report highlights an incremental approach to refining the grid over a series of experiments (in April and November 2015 and April 2016) to maximise the reductions in total bycatch and selected bycatch species of interest without affecting the targeted catch. This work represents a collaborative effort between the Spencer Gulf and West Coast Prawn Fishermen's Association, the South Australian Research and Development Institute (SARDI), the New South Wales Department of Primary Industries and IC Independent Consulting. While the project was undertaken to address bycatch issues specific to the SGPF, the incremental approach used to develop an optimal grid design has potential application among other prawn-trawl fisheries.

Background

Relative to other fishing methods, prawn trawling is considered to be poorly selective, and can result in large quantities of bycatch being discarded, which sometimes includes charismatic species. Attempts at reducing bycatch or mitigating trawl impacts to the discarded bycatch have involved three broad techniques: (1) avoidance by spatial and/or temporal closures; (2) on-board handling procedures that minimise the mortality of discarded bycatch; and (3) retrospectively fitting BRDs into trawls. The latter approach can be particularly effective, with some BRDs reducing bycatches by up to 90%.

One of the few remaining Australia prawn trawl fisheries that currently does not use any type of BRD is the SGPF. This fishery has been accredited by the Marine Stewardship Council in recognition of its effective management through a suite of controls within the first (fishing closures) and second (on-board handling) techniques above. Historically, these efforts have been sufficient to mitigate bycatch issues that have mostly involved Blue Swimmer Crabs (*Portunus armatus*), a key species targeted by other commercial and recreational trap fisheries in Spencer Gulf. At some locations in Spencer Gulf, trawlers can encounter large densities of Blue Swimmer Crabs, but all trawlers use a large-meshed 'crab bag' inside the codend, which effectively separates many crabs (and other large organisms) from Western King Prawns (*Melicertus latisulcatus*), and facilitates rapid discarding of the former, with assumed low mortality. But, despite the potentially low impact of trawling on discarded Blue Swimmer Crabs, their exoskeleton and claws are known to cause considerable damage to Western King Prawns as the latter pass through the crab bag, resulting in reduced quality and value of the targeted catch. Ideally, very few (if any) Blue Swimmer Crabs should enter the crab bag and codend.

Another species interaction with Spencer Gulf trawlers is that of the Giant Cuttlefish (*Sepia apama*). Unlike Blue Swimmer Crabs, Giant Cuttlefish are incidentally caught in relatively small quantities, but in recent years this species has attracted considerable attention when, in 2013, its annual spawning aggregation in northern Spencer Gulf (between May and July)—the largest known *Sepia* aggregation in the world—declined to record low levels. Several studies were undertaken on potential causes of the decline, but none provided any evidence that the SGPF had a detrimental impact. Nevertheless, due to the iconic status of Giant Cuttlefish and extent of the decline, all sources of potential mortality, including trawl bycatch, should be minimised.

Aims/objectives

The aim of this study was to test incremental technical refinements to a generic Nordmøre-grid[1] to identify an optimal design for the SGPF with respect to criteria of: (i) reducing total bycatch, with particular focus on maximising the escape of Blue Swimmer Crabs and Giant Cuttlefish; (ii) maintaining and improving the quality of Western King Prawn catches; and (iii) minimising technical handling issues in relation to the grid.

Methodology

A double-rigged trawler from the SGPF fleet was chartered for three experiments in northern Spencer Gulf over 13 nights (four in each of April 2015 and 2016, and five in November 2015). Each experiment involved paired comparisons between two or three grid configurations and a conventional codend (the control). Primary data collected from each codend were catch weights of Blue Swimmer Crabs, Giant Cuttlefish and broad categories for remaining bycatch (i.e. elasmobranchs, porifera, seagrasses/algae and teleosts), and Western King Prawns (including a breakdown by industry size grades and condition). The actual grid modifications tested in each experiment were determined intuitively, based on the assessment of catches by configuration in the preceding experiment (including the pilot study by Kennelly and Broadhurst 2014). In total, six grid configurations were tested over the course of the study; these were differentiated by the grid bar spaces, location of the horizontal support bar, area of the escape exit, and length of the guiding panel.

Results/key findings

The effects of varying grid bar spaces, escape-exit areas and guiding-panel lengths were investigated. Compared to a control, the greatest reductions (by weight) in total bycatch (~80%), Blue Swimmer Crabs and Giant Cuttlefish (both ~90%), and elasmobranchs and porifera (almost 100%), were achieved with a large, low-angled Nordmøre-grid with 38-mm bar spaces, a support bar two thirds up the length, a 2.7-m guiding panel terminating ~0.6 m anterior to the grid base, and a large escape exit ($\geq$0.8 m^2). Importantly, this configuration did not negatively impact catches of prawns, but rather improved their quality and value (presumably owing to fewer crabs causing less damage). In a global context, the reduction in total bycatch with the preferred grid was within the upper range of those observed for mechanical separators tested in other crustacean-trawl fisheries (typically 50–90%). These findings demonstrate the potential for improved selectivity in this fishery using a Nordmøre-grid—primarily by mechanical exclusion of bycatch from the target species owing to size and/or morphological differences.

Implications for relevant stakeholders

Assuming the performance of the preferred grid in this study applied to commercial trawling operations (with respect to reducing total bycatch, Blue Swimmer Crabs and subsequent damage to Western King Prawns, while maintaining the prawn catch), there is likely to be a net increase in value to the SGPF of ~A$0.4M and, in general, a positive ecological impact. The cost of supplies and labour required to fit a Nordmøre-grid is estimated at $1800 per net, although given the need for spares and that double-rigged trawlers are used throughout the fleet, multiple grids would need to be built per vessel. Inevitably, there also are likely to be additional variable costs associated with replacement, maintenance and repairs of grid components.

Recommendations

While the bycatch reductions achieved in this study are impressive by world standards, an area of concern for industry relates to the dimensions (~2 × 1 m) and weight (~24 kg) of the grid and the operational difficulties and safety concerns they may pose to the crew, particularly under fishing conditions worse than those experienced during the study (e.g. winds >35 km h^{-1}, swells >1.5 m).

[1] The generic Nordmøre-grid comprised a large (~2 × 1 m), low-angled grid located in the end of the trawl, and was designed to mechanically separate catches by allowing the targeted Western King Prawns to pass through and be retained, while directing the larger Blue Swimmer Crabs and Giant Cuttlefish upward and out through an escape exit.

Acknowledging these concerns, an appropriate next step would be to test the preferred grid across broader spatio-temporal scales on a number of vessels in the fishery under various conditions. By including operational data with catch assessments, it should be possible to objectively assess any concerns fishers have with using the grid and perhaps modify deployment and on-board handling procedures so they are more acceptable/suitable to industry operations.

Keywords

Blue Swimmer Crab (*Portunus armatus*), bycatch reduction device (BRD), Giant Cuttlefish (*Sepia apama*), selectivity, Western King Prawn (*Melicertus latisulcatus*)

1. Introduction

Relative to other fishing methods, penaeid-trawling is considered to be poorly selective, and can result in the discarding of large quantities of bycatch, which sometimes includes threatened or endangered species (Hall 1996; Kelleher 2005; Portley *et al.* 2015). The most common technique for mitigating penaeid-trawl bycatch is to install physical modifications in the posterior part of the trawl net, termed bycatch reduction devices (BRDs), which are designed to exclude organisms mainly based on differences in behaviour ('behavioural separators') or size ('mechanical separators') (Broadhurst 2000). Mechanical separators have been particularly successful in several fisheries, with designs like the 'Nordmøre-grid' consistently excluding up to 90% of total bycatch while maintaining catches of penaeids (Broadhurst *et al.* 1996; Brewer *et al.* 1998; Silva *et al.* 2011; Kennelly and Broadhurst 2014).

As for many penaeid-trawl fisheries over the past 20 years, those in Australia have made progressive attempts to refine mechanical separators to reduce the bycatch of various species of concern, including elasmobranchs and turtles (Brewer *et al.* 1998, 2006). Currently, many Australian penaeid-trawl fisheries use mechanical separators and virtually all require behavioural separators (e.g. Salini *et al.* 2000; Kennelly and Broadhurst 2002; Kangas and Thomson 2004; Courtney *et al.* 2006; Gorman and Dixon 2015). One of the few remaining Australian penaeid-trawl fisheries that currently does not use any type of BRD occurs in Spencer Gulf, South Australia. The Spencer Gulf Prawn Fishery (SGPF) has a history of testing several mechanical-separating BRDs (McShane 1997; Dixon *et al.* 2014), but while some significantly reduced bycatches, they did so inconsistently, and unacceptable losses (in general, greater than 10%) of the targeted Western King Prawn (*Merlicertus latisulcatus*) precluded their implementation.

The SGPF has employed, and continues to employ a range of strategies—both regulatory and voluntary—to manage the fishery, minimise bycatch and/or discard mortality, including historical reductions in fishing effort (by ~60% over the past 40 years), spatial and temporal closures and various on-board handling and discarding practices (PIRSA 2014b). These strategies, combined with strong industry governance (Gillett 2008; Zacharin *et al.* 2008), fishery-independent gulf-wide bycatch surveys (Currie *et al.* 2009; Burnell *et al.* 2015), ecological risk assessments (e.g. PIRSA 2014a) and few interactions with charismatic species of concern (like turtles; Carrick 1999), have enabled the SGPF to gain recognition by the United Nations' Food and Agricultural Organization (FAO) as one of the best-managed trawl fisheries in the world (Gillett 2008) and accreditation by the Marine Stewardship Council (MSC) (MRAG Americas Inc. 2016).

Currently, the fleet of the SGPF, which comprises 39 double-rigged trawlers (all using 2 × 14.6-m headline length trawls), typically trawl for ~50 nights per year (Noell and Hooper 2015) and within the same fishing grounds that account for ~20% of the gulf (Noell 2017). Fishers also are permitted to land Southern Calamari (*Sepioteuthis australis*) and Balmain Bugs (*Ibacus* spp.), with these collectively known as 'by-product'. All other incidentally caught species (bycatch) are discarded at sea. Among the discarded bycatch, the need to mitigate the bycatch of two species in particular—the Blue Swimmer Crab (*Portunus armatus*) and Giant Cuttlefish (*Sepia apama*)—has been evoked for different reasons.

At some locations in Spencer Gulf, trawlers can encounter large densities of Blue Swimmer Crabs (averaging ~6.9–7.7 kg ha^{-1} trawled; Currie *et al.* 2009; Burnell *et al.* 2015). Blue Swimmer Crab catches are highly variable, often comprise both adults and juveniles and, at some trawl grounds can be comparable to, or exceed catches of the targeted Western King Prawns. The same stock of Blue Swimmer Crabs is also exploited by commercial and recreational trap fisheries, with annual harvests in Spencer Gulf of ~380 and 290 t, respectively (Giri and Hall 2015; Beckmann and Hooper 2016). Due to the frequency of interactions with Blue Swimmer Crabs, and in an attempt to mitigate their mortalities, all trawlers use a large-meshed 'crab bag' inside the codend, which effectively separates many crabs (and other large organisms) from the prawns, and facilitates rapid discarding of the former, with assumed low mortality (~16%, based on estimates for another Australian fishery;

Wassenberg and Hill 1989, 1993). Notwithstanding few perceived impacts to discarded Blue Swimmer Crabs, their exoskeleton and claws cause considerable damage to Western King Prawns (and other soft-bodied species, e.g. Giant Cuttlefish) as these pass through the crab bag, reducing catch quality and value. Given the need to also separate Giant Cuttlefish (see below) from the targeted catch, the exclusion of Blue Swimmer Crabs is also important in terms of general BRD function, because any device that does not exclude Blue Swimmer Crabs may clog up with this species, negating its ability to exclude Giant Cuttlefish (and other bycatch species) and possibly contributing to a loss of the targeted catch. Ideally very few (if any) Blue Swimmer Crabs should enter the crab bag and codend.

Giant Cuttlefish are considered iconic in Australia and have attracted considerable attention in recent years because their annual spawning aggregation in northern Spencer Gulf (between May and July)—the largest known *Sepia* aggregation in the world—declined to record low levels in 2013 (Steer 2015). In response to this decline, several studies were instigated to investigate potential causes, including fishing pressure (Steer *et al.* 2013; Woodcock *et al.* 2014; Prowse *et al.* 2015). While some noted the incidental capture of Giant Cuttlefish in the SGPF, none of these studies provided any evidence to support the assertion that the decline had been caused by trawling. Subsequent increases in Giant Cuttlefish biomass were observed over successive years from 2014, and by 2016 had almost returned to pre-decline levels (Steer *et al.* 2016; SARDI, unpubl. data). Assuming these latter observations indicate a recovering Giant Cuttlefish population, the lack of any appreciable change in trawl intensity throughout the periods of decline and recovery for this species further suggest that the fishery is unlikely to have been the primary cause of the decline. Nevertheless, due to the iconic status of Giant Cuttlefish and extent to which its biomass had declined and over a rapid period, all sources of potential mortality, including that from prawn-trawl bycatch, was needed to be minimised where possible and carefully managed to protect the Giant Cuttlefish population.

Given the above, the fishing industry (i.e. licence holders) made a proactive decision to collaborate with researchers and managers to quantify (Steer 2015) and reduce its bycatch of Blue Swimmer Crabs and Giant Cuttlefish. As a first step towards addressing this need, Kennelly and Broadhurst (2014; FRDC 2013/052) conducted a pilot study in which trawl nets typically used in the SGPF were modified with the installation of Nordmøre-grids of various lengths, angles, flotation, etc. to mechanically exclude Blue Swimmer Crabs and Giant Cuttlefish from the catch. That study showed that a large (~1 × 2 m) low-angled (~30°) grid facilitated the escape of up to 34% (by number) of Blue Swimmer Crabs and *Sepia* spp.—comprising Giant Cuttlefish and the morphologically similar, but smaller New Holland Cuttlefish (*S. novaehollandiae*)—while maintaining catches of Western King Prawns. Although promising, these individual species/group reductions were not as large as those observed for Nordmøre-grids tested and developed in other fisheries (Broadhurst *et al.* 1996; Silva *et al.* 2011, 2012)—results that have been achieved through progressive design refinements of such grids.

A second stage to the project (the current study) was therefore required to make refinements to the generic design of Kennelly and Broadhurst (2014; FRDC 2013/052) to optimise its performance. Through rigorous testing of refined versions of these Nordmøre-grids, the ultimate aim of the current study was to produce an optimal design for potential implementation in the fishery.

2. Objectives

The aim of this study was to test incremental technical refinements to a large Nordmøre-grid (Kennelly and Broadhurst 2014; FRDC 2013/052) with respect to the criteria of: (i) reducing total bycatch, with particular focus on maximising the escape of Blue Swimmer Crabs and Giant Cuttlefish; (ii) maintaining and improving the quality of Western King Prawn catches; and (iii) minimising technical handling issues.

Based on variables shown to affect the performance of similar designs elsewhere (e.g. Silva *et al.* 2011, 2012), the specific objectives were to:

1. Assess alternative bar spacing and angles of the grid to determine the optimal design of the large Nordmøre-grid BRD that minimises the incidental catch of Blue Swimmer Crabs and Giant Cuttlefish, while maintaining conventional catches of Western King Prawns.
2. Assess alternative materials for the guiding panel to minimise clogging in the Nordmøre-grid.
3. Test the general applicability of the alternative Nordmøre-grid designs and modifications across months and regions of the fishery.
4. Recommend the optimal Nordmøre-grid design with respect to Objectives 1 to 3.

3. Methodology

Three experiments were done during 13 nights (four in each of April 2015 and 2016, and five in November 2015) using the same double-rigged trawler (FV *Lunar Sea*, 22 m and 336 kW; Fig. 1) in northern Spencer Gulf (Fig. 2). All experiments were done within traditional trawl grounds for Western King Prawns in depths of 10–30 m across sandy substrata, specifically in regions where Blue Swimmer Crabs and/or Giant Cuttlefish are known to occur. The trawler was rigged with two identical 'Gundry' trawl nets, each with a headline length of 14.6 m spread by flat-rectangular otter boards (1.7 × 1.1 m) and towed at ~1.9 m s^{-1}. Both posterior trawl bodies were fitted with zippers (Buraschi S146R, 2.0 m long) to facilitate changing the extensions/codends described below.

Fig. 1. The double-rigged trawler (FV *Lunar Sea*) chartered for the study.

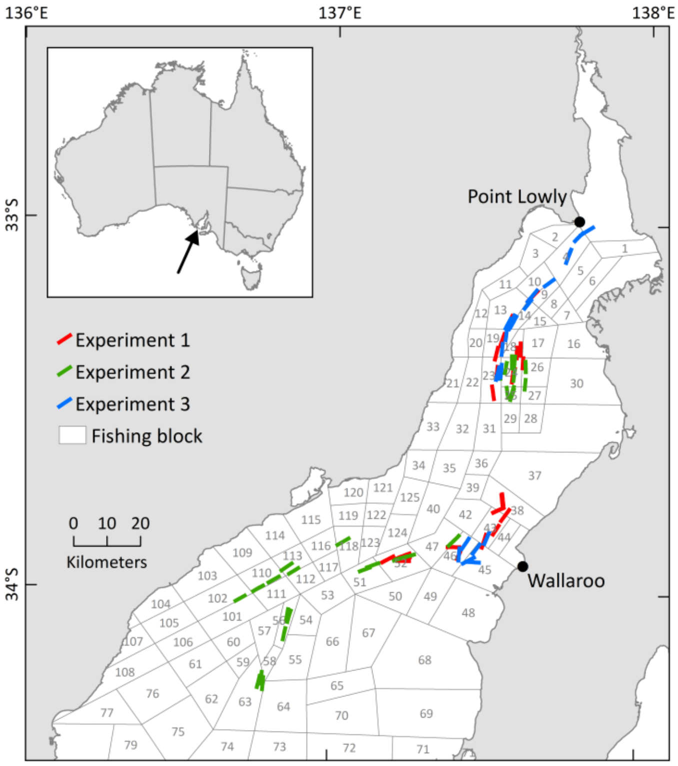

Fig. 2. Map of northern Spencer Gulf showing the trawl paths of the study. Also shown are commercial fishing blocks (polygons) of the Spencer Gulf Prawn Fishery. Inset map shows study location in Australia.

3.1. Nordmøre-grids and codends

One control (conventional) codend and six Nordmøre-grids and their extension sections/codends were constructed (Table 1; Fig. 3). The control comprised 41-mm (stretched mesh opening—SMO) mesh (2.2-mm diameter–Ø braided, green polyethylene–PE twine) measuring 105 meshes in the normal (N) direction and 150 meshes in the transverse (T) direction. Following conventional configurations, a cylindrical panel (termed a 'crab bag') of 150-mm SMO mesh (4.0-mm Ø braided green twine) and measuring 30 T × 6.5 N was inserted 32 N anterior to the last row of meshes in the codend to separate the larger Blue Swimmer Crabs from Western King Prawns (Fig. 3a).

Table 1. Specifications of the Nordmøre-grid treatments tested in each experiment. The 75- and 62-N guiding panels terminated at and 0.6 m anterior to the base of the grid, respectively.

Configuration	Experiment	Bar space (mm)	Horizontal support	Guiding panel length (m and no. of meshes)	Escape-exit taper and area (m^2)
35-mm grid	1	35.4	Mid-point	3.3 (75)	AB (0.4)
45-mm grid	1	45.0	Mid-point	3.3 (75)	AB (0.4)
AB-exit 75N-panel grid	2	38.2	Top third	3.3 (75)	AB (0.4)
1N2B-exit 75N-panel grid	2 and 3	38.2	Top third	3.3 (75)	1N2B (0.8)
1N2B-exit 62N-panel grid	3	38.2	Top third	2.7 (62)	1N2B (0.8)
1N1B-exit 62N-panel grid	3	38.2	Top third	2.7 (62)	1N1B (1.1)

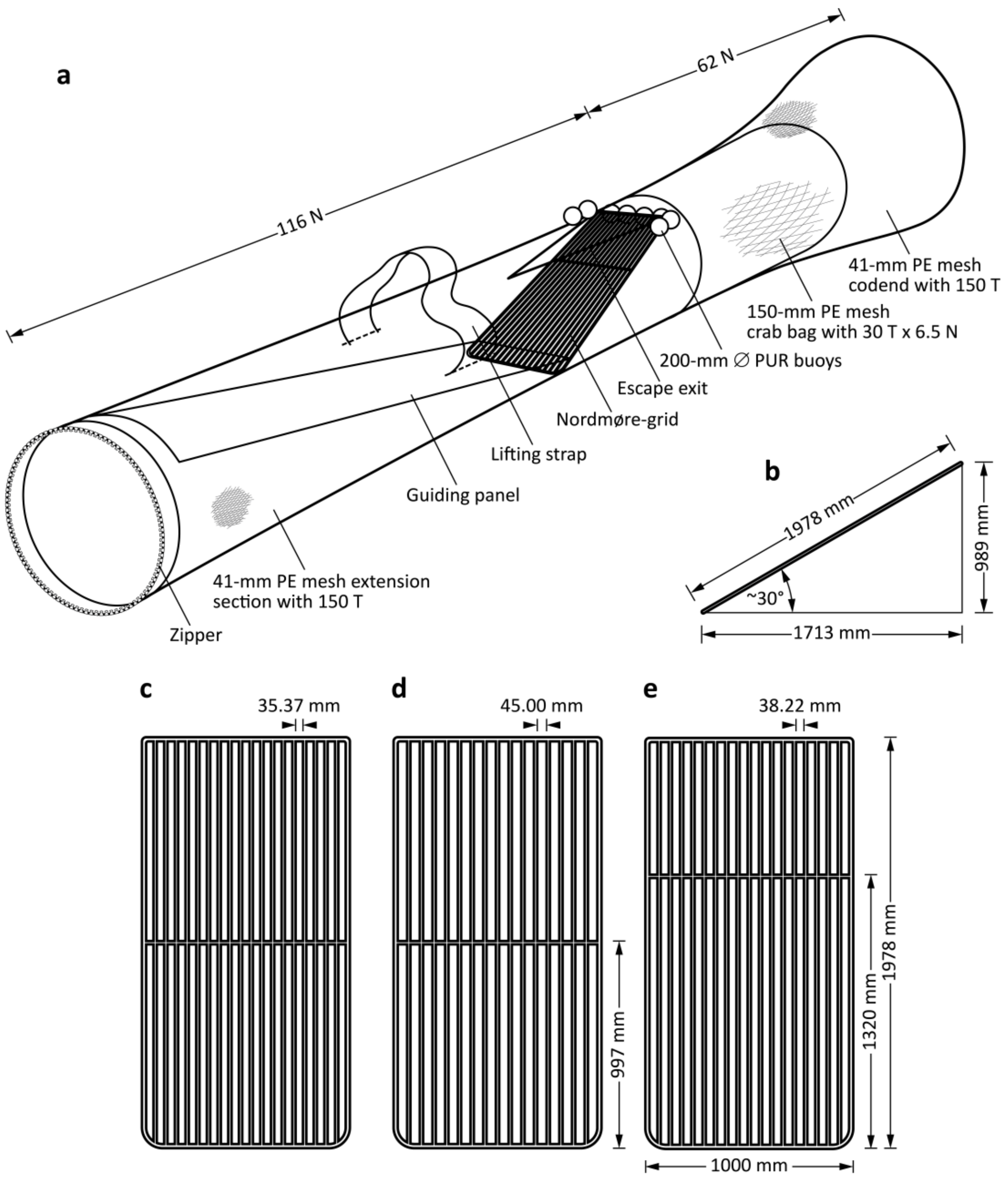

Fig. 3. Specifications of the (a) extension and codend (with crab bag) assembly with a Nordmøre-grid installed, (b) installation angle and (c) 35-, (d) 45- and (e) 38-mm grids tested. PE, polyethylene; PUR, polyurethane; T, transversals; N, normals; Ø, diameter.

All grids were flat, rectangular (1978 × 1000 mm) and constructed from solid aluminium rod (frame: 20-mm Ø; bars: 16-mm Ø) (Table 1; Fig. 3c–e). The key differences among grids were the spaces—dictated by the number of bars that could fit into the frame—and the location of a horizontal support (16-mm Ø rod) (Table 1; Fig. 3c–e). The first two grids (experiment 1) had 35.37- (termed the '35-mm grid') and 45.00-mm ('45-mm grid') bar spaces and a centre horizontal rod (Table 1; Figs 3c, d and 4). Based on their testing (see Results), the remaining four grids all had 38.22-mm bar spaces ('38-mm grid') and their horizontal support located closer to the top (Table 1; Fig. 3e).

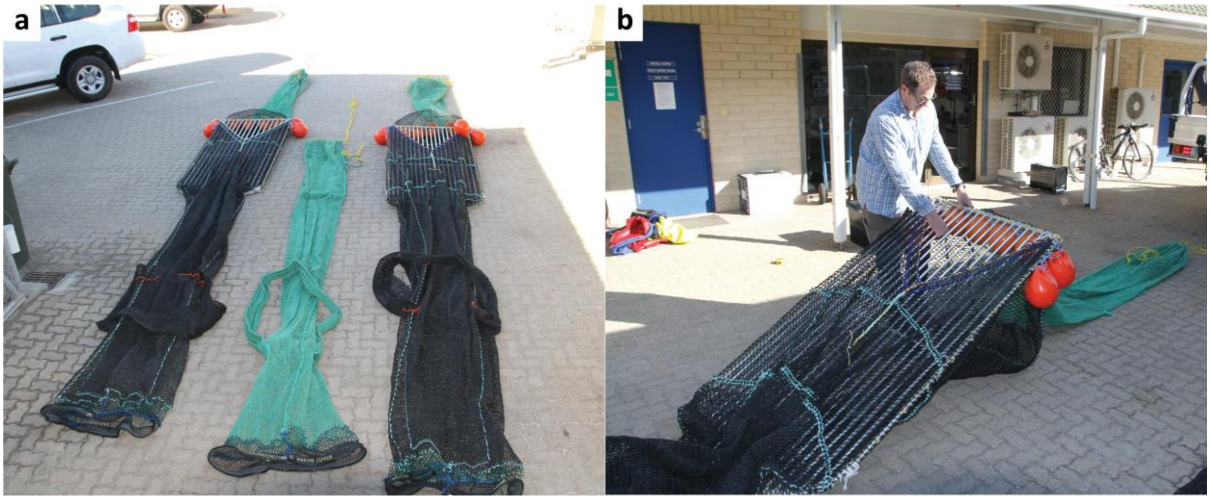

Fig. 4. The (a) 45-mm (left) and 35-mm (right) Nordmøre-grids and their extension sections/codends, either side of a control codend (centre), and (b) close-up of the 35-mm grid.

Each grid was inserted at ~30° (Fig. 3b) into an extension section made from 41-mm SMO mesh (3.0-mm Ø braided black PE twine) measuring 150 T × 116 N and with an anterior guiding panel (37.5 T wide; Table 1; Figs 3a and 5a–c). The 35- and 45-mm grids both had 75-N (~3.3 m) guiding panels terminating at the grid base and triangular escape exits measuring 37 bars (B) on each side, providing an opening of 0.4 m^2 (Table 1; Figs 3a and 5a, b).

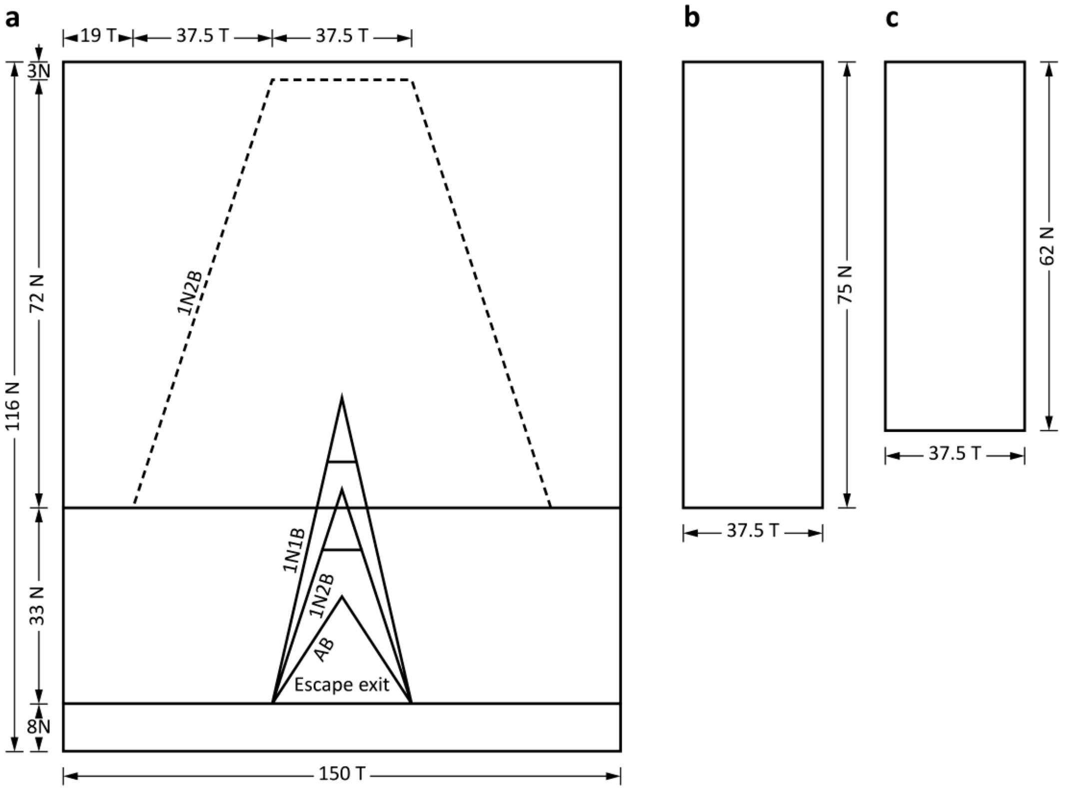

Fig. 5. Plans of the (a) extension cylinder showing the AB-, 1N2B- and 1N1B-exit openings, and (b) 75-N and (c) 62-N guiding panels. T, transversals; N, normal.

The four 38-mm grids differed in their escape-exit areas and/or guiding-panel lengths. The first and second 38-mm grids had a 75-N guiding panel (as above); but while the first had a triangular escape exit (termed the ‘AB-exit 75N-panel grid’), the second had an escape exit made by cutting forward 1N2B either side, to provide an opening of 0.8 m^2 (‘1N2B-exit 75N-panel grid’) (Table 1; Fig. 5a).

The third 38-mm grid also had a 1N2B escape exit, but with a shorter guiding panel (62 N and terminating 13 N or ~0.6 m anterior to the base of the grid; '1N2B-exit 62N-panel grid'), while the fourth 38-mm grid had a 1N1B escape exit (1.1 m^2) and the shorter guiding panel ('1N1B-exit 62N-panel grid') (Table 1; Fig. 5a, c).

Each Nordmøre-grid extension had lifting straps laterally attached 30 N anterior to the escape exit, sufficient 200-mm Ø polyurethane buoys (behind the top of the grid) to achieve neutral buoyancy, and a posterior codend (and crab bag) identical to the control, except it measured 62 N (Fig. 3a). Zippers were attached to all grid extensions and the control codend to facilitate attachment and removal from the two trawl bodies (Fig. 3a).

3.2. Experimental design

The control was tested with the (i) 35- and 45-mm grids in experiment 1, (ii) AB- and 1N2B-exit 75N-panel grids in experiment 2, and (iii) 1N2B-exit 75N-panel and 1N2B- and 1N1B-exit 62N-panel grids in experiment 3 (Table 1). During each experiment, the control and grids being tested were alternately zippered to the nets on each side of the vessel and towed for 30 min, which, compared to the average tow duration in the fishery of ~60 min, enabled more replicates to be completed, and was still considered long enough to obtain catches sufficient for testing configuration effects. On each night, at least three replicates of each configuration were attempted through all possible combinations of pairings, although in experiment 2, some deployments were done where a treatment or control was not paired (i.e. another grid configuration was attached but was later omitted from analysis due to its non-identical codend).

3.3. Data collected and statistical analyses

At the end of each deployment, the following data were collected from each codend: (i) total weights of Western King Prawns by industry categories (i.e. sorted using a Haldane PTY grading machine), including 'U8', 'U10', '10–15', '16–20' and '21–30' individuals per pound and 'soft and broken' (i.e. post-moult and/or damaged prawns); (ii) total weights of Southern Calamari and Balmain Bugs; (iii) total numbers, weights and, as an index of size in the absence of individual measurements, mean individual weights (total weight ÷ total number; Balash *et al.* 2016) for Blue Swimmer Crabs, Giant Cuttlefish and New Holland Cuttlefish; (iv) total weight of the remaining miscellaneous bycatch and its main components (elasmobranchs, porifera, algae/seagrasses and teleosts); and (v) numbers of individual teleost species. Representative subsampling was required to estimate the weights and numbers of Blue Swimmer Crabs and teleosts in the miscellaneous bycatch, and to measure total lengths (TL, rounded down to the nearest 0.5 cm) of teleosts. In addition to the above quantitative data, at the end of each deployment any debris that collected in the extensions or at the escape exits was noted and cleared and information describing on-board handling of the grids was collected. In the event of an unsuccessful deployment, the likely technical reason was noted (where possible) and the deployment was repeated.

Catch variables within each experiment were separately assessed in linear mixed models (LMMs) with all data log-transformed, except the mean individual weights of key species, so that the predicted effects would be multiplicative. The LMMs included 'configuration' as a fixed effect, while 'side' of the vessel, 'night' and the interaction between 'night' and 'deployment' (both of which were treated as factors) were included as random terms. Models were fitted using the ASReml-R package (Butler *et al.* 2009; R Core Team 2016) with the significance of configuration determined using a Wald F-statistic. Significant effects of configuration were subsequently explored using the Benjamini-Hochberg-Yekutieli procedure to control the false-discovery rate (FDR) for multiple pairwise comparisons (Benjamini and Hochberg 1995; Benjamini and Yekutieli 2001). Predicted means were back-transformed (where required from the log scale) to the original scale using the bias-correction formula of Sprugel (1983).

To facilitate interpreting results between sequential trials, the hypothesis of no inter-experimental (n = 3) differences in the mean individual weights of Blue Swimmer Crabs, Giant Cuttlefish and New

Holland Cuttlefish was also tested. In these analyses, LMMs were fitted to data from the control only, with ‘experiment’ fixed, and night and side used as random terms. Significant differences were separated as above.

4. Results

4.1. Fishing conditions, catches and variability in size among experiments

Weather conditions during the three experiments (12–34 km h^{-1} winds and <1.3 m seas) and catch rates were typical of those experienced during conventional fishing. When pooled across experiments (i.e. all 147 replicate tows), the partitioned catches comprised 7152, 330 and 7377 kg of Western King Prawns, by-product (Southern Calamari and Balmain Bugs combined) and bycatch, respectively (Appendix 3, Table A-5). Blue Swimmer Crabs, Giant Cuttlefish and New Holland Cuttlefish comprised 32.5%, 2.1% and 0.9% of the total bycatch weight, respectively. While Blue Swimmer Crabs and New Holland Cuttlefish maintained consistent trends between experiments, Giant Cuttlefish were more abundant during experiments 1 and 3.

Inter-experimental variability among the relative sizes of Western King Prawns was minimal for the control (>60% of the catches had 16–30 individuals per pound; Fig. 6). But the mean individual weight of Blue Swimmer Crabs was significantly less in experiment 1 (100 ± 12 g) than experiment 2 (147 ± 12 g) (LMM and FDR, $p < 0.05$; Fig. 7). By comparison, there were no significant differences in the mean individual weights of (i) Blue Swimmer Crabs between experiments 2 (147 ± 12 g) and 3 (136 ± 13 g) (LMMs and FDRs, $p > 0.05$), (ii) Giant Cuttlefish between experiments 1 (432 ± 37 g) and 3 (489 ± 42 g) (too few were caught in experiment 2 – see below), or (iii) New Holland Cuttlefish among all three experiments (predicted means between 84 ± 15 and 102 ± 12 g) (Fig. 7).

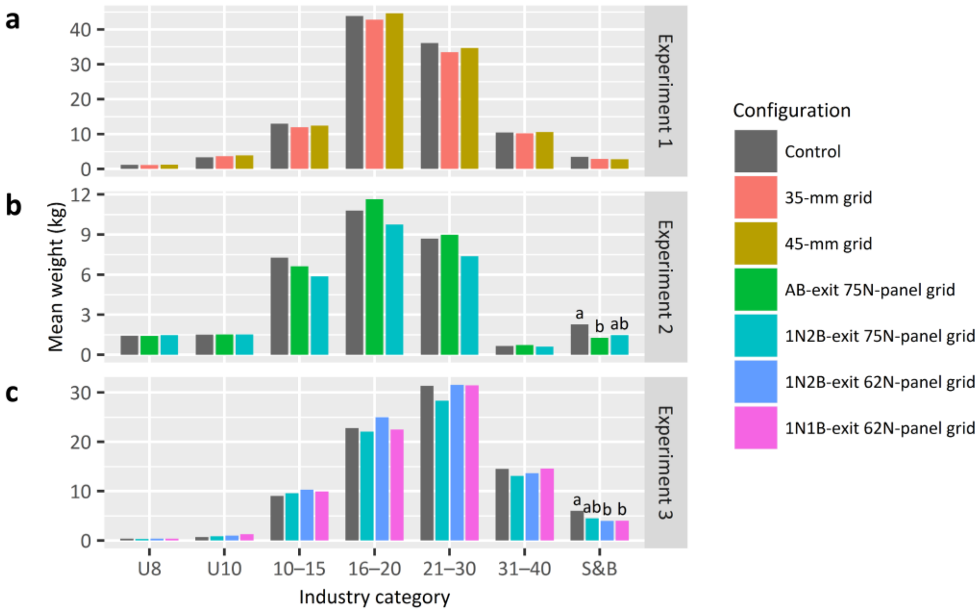

Fig. 6. Predicted mean industry category weights 30 min^{-1} of Western King Prawns by configuration for experiments (a) 1, (b) 2 and (c) 3. Where there was a significant effect ($p < 0.05$) among configurations within an experiment, letters above bars denote the false-discovery-rate (FDR) adjusted pairwise comparisons ($p < 0.05$). Note the different y-axis scales between experiments.

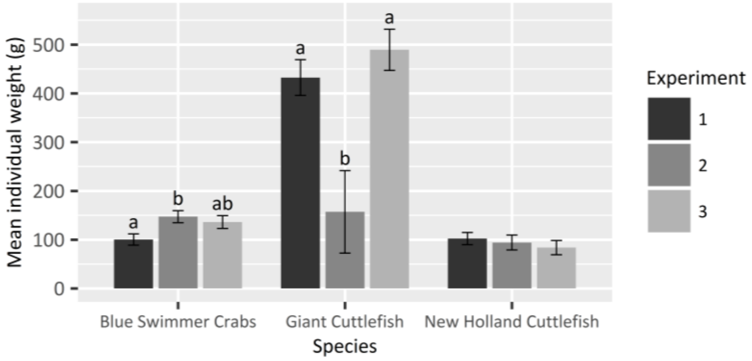

Fig. 7. Predicted mean individual weights (± SE) of Blue Swimmer Crabs, Giant Cuttlefish and New Holland Cuttlefish from the control codend of each experiment. Where there was a significant effect ($p < 0.05$) among experiments for a particular species, letters above bars denote the false-discovery-rate (FDR) adjusted pairwise comparisons ($p < 0.05$).

The remaining bycatch in all three experiments comprised a similar suite of species, comprising at least 48 teleosts, 11 chondrichthyans, 6 cephalopods, 6 crustaceans, 4 bivalves and 3 echinoderms (Appendix 3, Table A-5). Of the teleosts caught in all experiments, most (90%) were small (<14 cm TL) monacanthids—predominantly Rough Leatherjacket (*Scobinichthys granulatus*) and Bluefin Leatherjacket (*Thamnaconus degeni*), Skipjack Trevally (*Pseudocaranx wrighti*), Elongate Bullseye (*Parapriacanthus elongatus*), Bluespotted Goatfish (*Upeneichthys vlamingii*), Spotted Dragonet (*Repomucenus calcaratus*) and Silverbelly (*Parequula melbournensis*) (Table S1). Linear mixed models did not detect significant reductions in catches of these teleosts by any of the six Nordmøre-grids ($p > 0.05$; Table 2), except for Skipjack Trevally in experiment 2; nor was there any visual evidence for a configuration effect on the length-frequency distributions in these catches (Fig. 8).

Table 2. Linear mixed model Wald *F*-values for the fixed effect of trawl configuration on log-transformed catches from experiments 1, 2 and 3. Western King Prawn industry categories are counts per pound (454 g). U8 and U10, under 8 or 10 prawns per pound, respectively; **p* < 0.05; ***p* < 0.01; ****p* < 0.001; †, insufficient data for analysis.

Variable	Experiment 1	Experiment 2	Experiment 3
Retained catches			
Wt of Western King Prawns			
U8	0.20	0.04	0.77
U10	0.74	0.00	3.15*
10–15	0.93	2.25	0.71
16–20	0.44	1.36	1.16
21–30	0.52	3.69	1.05
31–40	0.17	0.71	1.24
Soft and broken	2.76	5.14*	5.45**
Total	0.61	2.73	1.03
By-product			
Wt of Southern Calamari	0.11	0.52	0.26
Wt of Balmain Bugs	11.64***	1.70	30.85***
Discarded catches			
Key invertebrates			
No. of Blue Swimmer Crabs	16.14***	14.76***	17.59***
Wt of Blue Swimmer Crabs	27.67***	15.74***	33.00***
Mean individual wt of Blue Swimmer Crabs	3.14	4.00*	11.22***
No. of Giant Cuttlefish	5.86**	0.09	21.35***
Wt of Giant Cuttlefish	12.41***	0.20	20.08***
Mean individual wt of Giant Cuttlefish	8.14**	†	3.64*
No. of New Holland Cuttlefish	1.21	3.04	1.51
Wt of New Holland Cuttlefish	0.42	3.14	0.99
Mean individual wt of New Holland Cuttlefish	2.51	0.10	0.09
Most abundant teleosts (rank 1–6)			
No. of monacanthids	0.62	0.73	0.18
No. of Skipjack Trevally	0.45	4.74*	0.74
No. of Elongate Bullseye	0.31	1.26	0.60
No. of Bluespotted Goatfish	0.05	0.11	2.74
No. of Spotted Dragonet	1.06	1.62	1.68
No. of Silverbelly	1.33	0.06	2.13
Main taxonomic groups			
No. of elasmobranchs	18.78***	7.07**	95.28***
Wt of elasmobranchs	29.24***	60.86***	171.60***
Wt of porifera	28.40***	10.50***	37.47***
Wt of algae and seagrasses	0.34	2.07	1.29
Wt of teleosts	1.11	0.78	0.12
Total bycatch			
Wt of total bycatch	40.61***	42.89***	48.73***

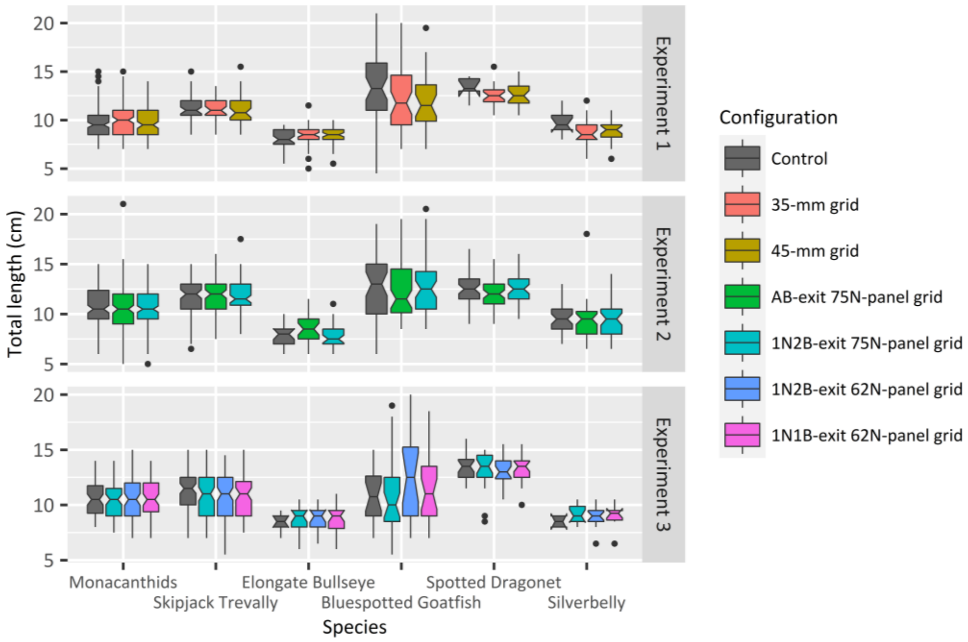

Fig. 8. Notched box plots showing length-frequency distributions of the six most abundant teleost species/groups (in descending order) by configuration for experiments (a) 1, (b) 2 and (c) 3. The boxes extend from Q1 to Q3 (the inter-quartile range, IQR), the whiskers extend to Q1-1.5*IQR and Q3+1.5*IQR, and the notches indicate 95% confidence interval for comparing medians.

4.2. Experiment 1: Assessing bar spaces

Despite the large size of the grids, few technical problems were encountered, with two deployments (one for each grid) repeated after the extension twisted during setting. However, debris was occasionally observed wedged between the top of the grid and the sides of the escape exit, which required cleaning. Where possible, this debris was retrieved on deck and included in catches of the main taxonomic groups. Although on-board handling of the grids was mostly straightforward, in one deployment a rock became dislodged and fell through the escape exit while the codend was being emptied.

No significant differences were detected among configurations for any of the industry categories or total weights of Western King Prawns, although slightly lower total catches were predicted with the 35-mm grid (by 4%) than either the 45-mm grid or control (LMM, $p > 0.05$; Table 2; Fig. 9a). These results precipitated a decision to test the 38-mm bar space in subsequent experiments (Table 1). By comparison, significant configuration effects were detected for the numbers and weights of Blue Swimmer Crabs and elasmobranchs, the number and weight of Giant Cuttlefish, and their mean individual weight, and weights of Balmain Bugs, porifera and total bycatch (LMMs, $p < 0.01$; Table 2). No other variables (including all teleosts) were significantly affected by configuration (LMM, $p > 0.05$).

False-discovery rate pairwise comparisons revealed that, compared to the control, trawls with the 35- and 45-mm grids similarly retained significantly lower numbers and weights of Blue Swimmer Crabs (predicted means reduced by up to 67% and 56%, respectively) and elasmobranchs (up to 96% and 97%), weights of Giant Cuttlefish (73% and 52%) at smaller individual weights (428 ± 40 vs 272 ± 41 and 294 ± 40 g), and weights of Balmain Bugs (88% and 80%), porifera (91% and 89%) and total bycatch (61% and 52%) ($p < 0.05$; Figs 9b–g and 10a; see Fig. 11 for example of total bycatch reduction). The only variable not similarly affected was the number of Giant Cuttlefish, with a significant reduction (56%) by the 35-mm grid only (FDR, $p < 0.05$).

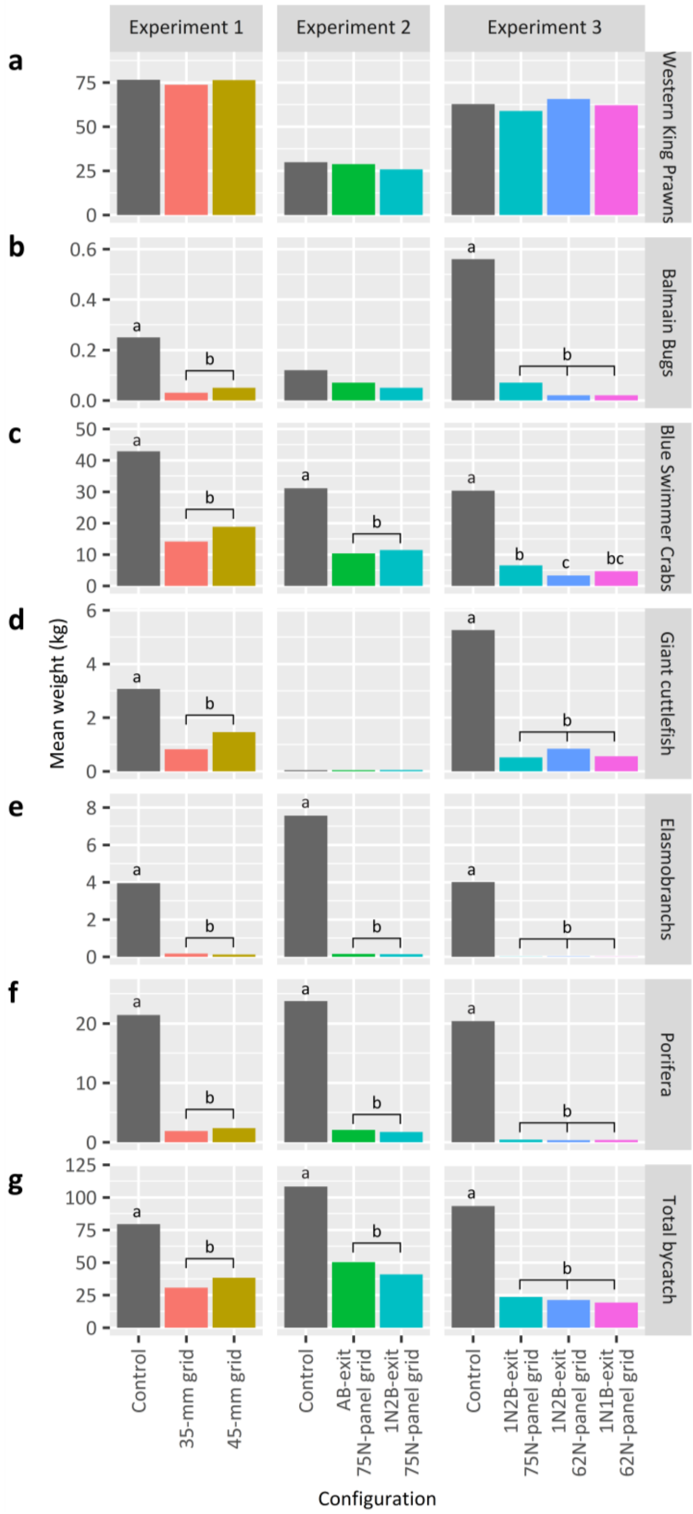

Fig. 9. Predicted mean catch weights 30 min^{-1} of (a) Western King Prawns, (b) Balmain Bugs, (c) Blue Swimmer Crabs, (d) Giant Cuttlefish, (e) elasmobranchs, (f) porifera and (g) total bycatch by configuration and experiment. Where there was a significant effect ($p < 0.05$) among a species/group within an experiment, letters above bars denote the false-discovery-rate (FDR) adjusted pairwise comparisons of the configurations ($p < 0.05$).

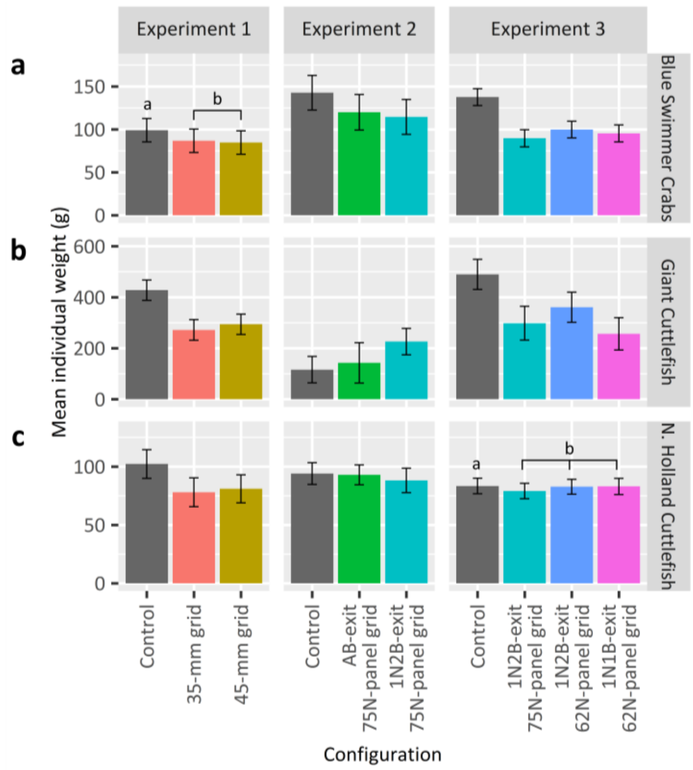

Fig. 10. Predicted mean individual weights (± SE) of (a) Blue Swimmer Crabs, (b) Giant Cuttlefish and (c) New Holland Cuttlefish by configuration and experiment. Where there was a significant configuration effect ($p < 0.05$) among a species within an experiment, letters above bars denote the false-discovery-rate (FDR) adjusted pairwise comparisons ($p < 0.05$).

Fig. 11. An example of comparative catches by the 35-mm Nordmøre-grid (left) and the control codend (right).

4.3. Experiment 2: Assessing escape-exit area

To alleviate the risk of injury from falling debris during retrieval, the crew routinely checked the grid extensions and, as required, extracted debris and brushed the grid clean as the extension was hauled aloft. There were no deployment or on-board handling issues, and clearly less clogging around the frame line of the 1N2B-exit grid than that with the smaller AB-exit. No weed/debris accumulated near the base of the grid with the horizontal support at the top third.

As in experiment 1, LMMs failed to detect significant differences among configurations for the industry categories and total weights of Western King Prawns ($p > 0.05$), except for those that were soft and broken, with a 44% lower predicted mean catch by the AB-exit 75N-panel grid than the control (FDR, $p < 0.05$; Fig. 6b). Notwithstanding the above, there also was a trend of smaller total catches of Western King Prawns with the 1N2B-exit 75N-panel grid than the control (by 14%; Fig. 9a).

Significant configuration effects were detected for a similar set of bycatch species/groups to those identified in experiment 1, including the numbers and weights of Blue Swimmer Crabs and elasmobranchs, and weights of porifera and total bycatch, but also the mean individual weight of Blue Swimmer Crabs and number of Skipjack Trevally (LMMs, $p < 0.05$; Table 2). No other bycatch species were affected by configuration (LMMs, $p > 0.05$; Table 2). Unlike in experiment 1, there were no significant effects of configuration on the weights of Balmain Bugs or the number, weight and mean individual weight of Giant Cuttlefish (LMMs, $p > 0.05$; Table 2). However, both species were retained in low densities (i.e. <1 per deployment) across the trawled area.

In terms of the directions of significant differences, compared to the control, the AB- and 1N2B-exit 75N-panel grids caught significantly lower numbers and weights of Blue Swimmer Crabs (by up to 67% and 63%, respectively) and elasmobranchs (up to 98% for both grids), and weights of porifera (91% and 93%) and total bycatch (54% and 62%) (FDRs, $p < 0.05$; Fig. 9c, e–g). The only variables not similarly affected were the number of Skipjack Trevally, with significantly fewer (by 59%) caught by the 1N2B-exit 75N-panel grid than the AB-exit 75N-panel grid only (FDR, $p < 0.05$) and the mean individual weight of Blue Swimmer Crabs, which could not be separated, although the 1N2B-exit 75N-panel grid caught smaller Blue Swimmer Crabs (115 ± 20 g) than the AB-exit 75N-panel (120 ± 21 g) or control (143 ± 20 g) (FDR, $p > 0.05$; Fig. 10a).

4.4. Experiment 3: Assessing escape-exit area and guiding panel length

No technical issues were experienced with the three grids, except for one deployment needing to be repeated when the 1N2B-exit 72N-panel grid codend was empty (possibly owing to the trawl being twisted during deployment and not achieving bottom contact). There were also few issues with clogging among the grids, particularly for the 1N2B- and 1N1B-exit 62N-panel grids.

Similar to experiment 2, a significant configuration effect was detected for soft and broken Western King Prawns (LMM, $p < 0.01$; Table 2), where lower weights were predicted with the 1N2B-exit and 1N1B-exit 62N-panel grids (34 and 33%, respectively) than the control (FDR, $p < 0.05$; Fig. 6c). The only other prawn category significantly affected by configuration was the U10 (LMM, $p < 0.05$; Table 2); however, this was not separated by the FDRs ($p > 0.05$; Fig. 6c). By comparison, significant configuration effects were detected for the numbers, weights and mean individual weights of Blue Swimmer Crabs and Giant Cuttlefish, number and weight of elasmobranchs, and weights of Balmain Bugs, porifera and total bycatch (LMMs, $p < 0.05$; Table 2).

Compared to the control, the 1N2B-exit 75N-panel grid and the 1N2B- and 1N1B-exit 62N-panel grids caught significantly lower numbers and weights of Blue Swimmer Crabs (by up to 78%, 89% and 84%, respectively), Giant Cuttlefish (up to 90%, 84% and 89%) and elasmobranchs (up to 100% for all grids), and weights of Balmain Bugs (88%, 96% and 96%), porifera (98% for all grids) and total bycatch (75%, 77% and 79%) (FDRs, $p < 0.05$; Fig. 9b–g). The only significant difference between grids was for the number and weight of Blue Swimmer Crabs, with the 1N2B-exit 62N-panel grid catching fewer than the 1N2B-exit 75N-panel grid (by up to 55%) (FDR, p < 0.05; Fig. 9c).

The three grids similarly retained smaller Blue Swimmer Crabs (90 ± 10, 100 ± 10 and 95 ± 10 g) than the control (138 ± 10 g) (FDR, p < 0.05; Fig. 10a). While the 1N1B-exit 62N-panel grid also retained smaller Giant Cuttlefish (257 ± 64 g) than either the 1N2B-exit 75N-panel grid (298 ± 66 g), 1N2B-exit 62N-panel grid (361 ± 59 g) or control (489 ± 59 g), these differences were not significant (FDR, p > 0.05; Fig. 10b). No other significant differences were detected (LMM, p > 0.05; Table 2).

5. Discussion

The results from the current study demonstrate the utility of cumulatively assessing technical changes to a generic Nordmøre-grid configuration to approach a desired selectivity. The total bycatch reduction by the optimal design (~80% by weight) was within the upper range of those observed for mechanical separators tested in other crustacean-trawl fisheries throughout the world (typically 50–90%; Broadhurst *et al.* 1996; Brewer *et al.* 1998; Fonseca *et al.* 2005; Grimaldo 2006; Silva *et al.* 2011; Kennelly and Broadhurst 2014). Further, the relative numbers of Blue Swimmer Crabs and Giant Cuttlefish excluded by Kennelly and Broadhurst (2014) were more than doubled in the current study from ~35 to >80%, with no loss of Western King Prawns. These findings can be discussed in terms of species-specific morphologies and possible behavioural/mechanical responses to the various refinements.

5.1. Grid evolution and possible escape mechanisms

Experiment 1 focused on identifying the optimal bar spacing between two grids: one with 35 mm, considered to be near the limit at which the largest Western King Prawns would be affected (e.g. 39–49 mm carapace length with maximum carapace widths of 18–23 mm; King 1977; SARDI, unpubl. data); and the other with 45 mm, tested by Kennelly and Broadhurst (2014). Neither grid significantly affected the catches of Western King Prawns (although the 35-mm grid retained slightly fewer in total), which largely can be attributed to the long, low-angled guiding panel directing the catch to the base of the similarly angled grid. This configuration provided minimal directional transition and clogging before sorting occurred across the entire surface of the grid (Broadhurst *et al.* 1996; Silva *et al.* 2011; Kennelly and Broadhurst 2014). Such a process clearly was sufficient for all Western King Prawns to be more-or-less passively orientated parallel to the bars and pass through (considering their limited response to trawls; Watson 1989); and this occurred despite a relatively (to many other penaeid fisheries) fast towing speed of ~1.9 m s^{-1}.

Like Western King Prawns, Giant Cuttlefish would have had considerable exposure to the grid surfaces and, considering their poor swimming speed, many also were probably orientated parallel to the bars. Consequently, their selection simply would have been a function of their mantle dimensions which, for experiment 1, meant only the 35-mm grid significantly reduced numbers. Blue Swimmer Crab exclusion would also be size-dependent, but their considerable morphological complexity means that spaces in the grids were likely to be less selective than for Western King Prawns or Giant Cuttlefish.

In comparison, none of the teleosts caught were affected by the different bar spaces in experiment 1. Given that most teleosts were <14 cm TL and laterally compressed with widths considerably less than 35 mm, all simply passed through the grids. But, in terms of physical capabilities, many of these fish theoretically should have been able to avoid the grid if they had sufficient time to respond. Specifically, considering the horizontal distance of the grid (~1.7 m) and towing speed (~1.9 m s^{-1}), organisms would need to swim a vertical distance of ~1.0 m at a speed of at least ~1.1 m s^{-1} to encounter the escape exit. Such swimming speeds should encompass the capabilities of most sizes caught (Wardle 1989). Further, the proximity of the crab bag (~1 m) to the exit opening should have anteriorly displaced water (and caused a reduction in perceived flow), thereby assisting small teleosts to swim (Broadhurst *et al.* 2012).

Considering the above, the lack of any behavioural escape by the teleosts implied insufficient visual cues and that bar spaces would have to be considerably narrower (or perhaps more visual) to affect their catches. Although not significant, narrower bars in the 35-mm grid promoted the escape of more Giant Cuttlefish, but the slight reduction in catches of Western King Prawns implied concomitant losses with any further narrowing of spaces. For this reason, a bar spacing of ~38 mm was chosen as a compromise for the subsequent experiments (i.e. those that compared different escape-exit openings and guiding-panel lengths).

Within the 38-mm grids, increasing the escape-exit opening also failed to affect teleost catches, although the predicted means for some of the abundant species varied and, in some cases, with greater numbers caught using the grid(s) than the control. Inspection of LMM residuals did not reveal any explanation for these inconsistent results; nonetheless, it was difficult to reconcile whether the larger-exit grids facilitated the escape of more teleosts.

Escape-exit area similarly had no apparent effects on Western King Prawns, except for the soft and broken category, where lower weights were predicted with the AB- and 1N2B-exit 75N-panel grids (although the latter was not significant). Such a result presumably reflects fewer damaged Western King Prawns due to the reductions of Blue Swimmer Crabs in catches (Gorman and Dixon 2015).

Giant Cuttlefish were encountered at low densities during experiment 2, precluding any assessment of their responses to the revised grids. Further, few insights were gained from the more consistently abundant New Holland Cuttlefish owing to the large inter-specific size difference. Therefore, the 1N2B-exit opening grid was reassessed in experiment 3, but with a further increase in the exit opening and reduction in the guiding panel length. The rationale for these changes was to increase the opportunities for anterior escape by reducing contact distance with the grid (Broadhurst 2000).

Consistent with the earlier experiments, configuration effects were detected in experiment 3 for the same bycatch species/groups (i.e. numbers and weights of Blue Swimmer Crabs, Giant Cuttlefish and elasmobranchs, and weights of porifera and total bycatch). The actual refinements appeared to be particularly beneficial in that all three Nordmøre-grids yielded the largest reductions in these categories for the whole study, while also maintaining Western King Prawn catches. With no one particular Nordmøre-grid consistently outperforming the others across all bycatch categories, the small variations manifested as slightly greater, but non-significant, reductions in total bycatch with each refinement.

An important consideration in interpreting the above observations is the potential for inter-experimental confounding of the sizes of organisms caught. Specifically, the mean individual weight of Giant Cuttlefish was larger in experiment 3 than in experiment 1; however, given that the difference was not significant, confounding effects might be small, particularly when compared to the disproportionately greater exclusion between configurations.

5.2. Economic and ecological benefits of using Nordmøre-grids

The catch dynamics associated with the tested Nordmøre-grids also revealed that an economic benefit should accrue to the SGPF as a result of retaining fewer Blue Swimmer Crabs in trawls and presumed reductions in the associated damage to Western King Prawns. Densities of both species are temporally and spatially variable, making extrapolations difficult. But, if the reduction in the soft and broken category of Western King Prawns was proportionally allocated among all sizes, then based on recent landings and prices (Noell *et al.* 2015; SARDI, unpubl. data) Nordmøre-grids would increase value to the fishery by some A$0.44M per year. Such revenue would more than offset any concomitant loss of Balmain Bug catches (~A$0.04M per year).

The net impact of using the Nordmøre-grids on the Blue Swimmer Crab stock is less clear. While reductions in the bycatch of any species might normally be assumed to benefit subsequent stock(s), there is an absence of data on the fate of Blue Swimmer Crabs escaping grids and some evidence of increased productivity of this scavenger species with trawl intensity (McShane *et al.* 1999; Currie *et al.* 2009; Burnell *et al.* 2015)—the latter presumably due to higher volumes of discards being available as food, including its conspecifics via cannibalism. Notwithstanding the uncertainty of how the Blue Swimmer Crab stock might be impacted, the reduction in the remaining bycatch (i.e. excluding Blue Swimmer Crabs) using the Nordmøre-grids—estimated by deduction to be in the order of 70–80%—is likely to have some positive ecological impacts.

5.3. Technical considerations and future research

Throughout the study, there were few issues with debris clogging the extensions or grids or repeated deployments due to twisting of the extension section (2% of replicate tows). With more experience using grids, fewer issues may arise. However, while a large grid appears to be a fundamental design component of a BRD for this fishery (Kennelly and Broadhurst 2014), the skipper noted this also made it cumbersome. Like many other fishers who are new to using such modifications, the Spencer Gulf prawn fishers are apprehensive of large mechanical-type separators due to operational and safety concerns. Acknowledging these concerns, a next phase in this work would be to undertake trials of the preferred grid system (i.e. the 1N2B- or 1N1B-exit 62N-panel grid) across broader spatio-temporal scales and with more fishers in the fishery. Further refinements to the 62N-panel grid design involving fabrication with lighter materials, like polymers, may be worthwhile. By including operational data with the assessment of catches, it should be possible to objectively assess any concerns fishers have with using the system and perhaps modify deployment and on-board handling procedures so that they are more acceptable to industry.

6. Conclusion

In general, the objectives of the study were addressed, although, as the study evolved, variations occurred in two areas:

1. Although certain modifications were anticipated at the beginning of the study (i.e. bar spacing, grid angle and guiding panel material, as specified in Objectives 1 and 2), the actual refinements tested in each experiment were determined intuitively, based on the interpretation of results of the previous experiment. In the end, work was done to identify an optimal bar spacing for the grid (experiment 1; as intended in Objective 1), and assess the utility of increasing the escape-exit area (experiments 2 and 3) and shortening the guiding panel (experiment 3).
2. The number of available nights, designs tested and replicates per night meant that there was limited scope to formally test designs and modifications across months and regions of the fishery (as intended in Objective 3). We suggest that, to address this objective adequately, a next phase for this work would be to undertake trials of the preferred grid design (Objective 4) across broader spatio-temporal scales and with more fishers in the fishery.

Combined with previous work (Kennelly and Broadhurst 2014), the current study highlights an incremental approach to the development of a Nordmøre-grid, whereby technical refinements were made over a series of experiments to identify the best grid configuration for the SGPF with respect to maximising reductions of Blue Swimmer Crabs, Giant Cuttlefish and total bycatch, while maintaining Western King Prawn catches. The greatest reductions of Blue Swimmer Crabs, Giant Cuttlefish, elasmobranchs, porifera and total bycatch (with no loss of prawns) were achieved by a large, low-angled Nordmøre-grid with 38-mm bar spaces, a support bar two thirds up the length, a guiding panel terminating ~0.6 m anterior to the grid base, and a large escape exit (with an opening of at least 0.8 m^2). Further, probably due to fewer Blue Swimmer Crabs being caught, damage to Western King Prawns was reduced, resulting in a better quality and value of the retained target species. These results demonstrate the potential for improved selectivity in this fishery using a Nordmøre-grid—primarily by mechanical exclusion of bycatch species from the target species largely owing to size and/or morphological differences.

7. Implications

Expected economic and ecological benefits of using the preferred Nordmøre-grid are outlined in Section 5.2. Assuming the performance of the grid translated to commercial trawling—with respect to reducing total bycatch, Blue Swimmer Crabs and subsequent damage to Western King Prawns, while maintaining the prawn catch—there is likely to be an increase in value to the SGPF of ~A$0.4M and, in general, a positive ecological outcome.

The cost of supplies and labour required to build the extension section (comprising a cylindrical panel, guiding panel, Nordmøre-grid, floats and zippers) was ~$1800; although given the need for spares and that double-rigged trawlers are used throughout the fleet, multiple extension sections would need to be built per vessel. While these costs can reliably be estimated, there inevitably will be additional variable costs associated with replacement, maintenance and repair of the extension section. Ideally, such work would be done on land since the entire fleet fish on the same nights, and so missed opportunities for any vessel to fish due to time spent at sea doing other activities would result in further loss of revenue.

8. Recommendations for further development

The bycatch reductions achieved in this study using the preferred grid—~80% for total bycatch, ~80–90% for Blue Swimmer Crabs and Giant Cuttlefish, and almost total exclusion (~100%) of elasmobranchs and porifera—are impressive by world standards. However, based on feedback from the skipper, an area of concern for industry relates to the dimensions (~2 × 1 m) and weight (~24 kg) of the grid and the operational difficulties and safety concerns they may pose to the crew, particularly under fishing conditions worse than those experienced during the study (e.g. larger tides and amounts of natural debris such as seagrass and algae, stronger winds and higher seas).

Acknowledging these concerns, an appropriate next step would be to test the preferred grid across broader spatio-temporal scales on a number of vessels in the fishery. By including operational data with the assessments of catches, it should be possible to objectively assess any concerns fishers have with using the grid and perhaps modify deployment and on-board handling procedures so that they are more acceptable to industry. In this regard, lessons may also be learned from the implementation of similar BRDs in other Australian fisheries. For example, the Northern Prawn Fishery have been using turtle excluder devices (TEDs)—comparable in size to the Nordmøre-grids tested in this study—for more than 15 years. Presumably, during the development of these TEDs, fishers would have experienced similar issues to those identified above and alleviated subsequent concerns through some modification to their fishing operations.

Another area of research and development that may warrant perusal is suitability of grid material. Specifically, industry might require a stronger and lighter material (e.g. like the polymer used for grids in the adjacent Gulf St Vincent prawn fishery). The bar rods ideally would need to be of the same diameter tested in this study to obtain similar results; otherwise, if they are thicker, spaces will be replaced by solid material, which may result in loss of Western King Prawns. If it is necessary to use thicker bars to increase strength, then this (or any other) modification would need to be tested in line with, and as an extension of, the incremental approach highlighted by Kennelly and Broadhurst (2014) and in the current study.

9. Extension and adoption

Since the development of the research proposal, this project has been a standing agenda item at monthly meetings of the Spencer Gulf and West Coast Prawn Fishermen's Association's (SGWCPFA) Management Committee; the membership of which comprises an Independent Chair, Executive Officer and licence holders representing industry, the Prawn Fisheries Manager (Primary Industries and Regions South Australia) and Research Scientist (Crustaceans) (i.e. the Principal Investigator, PI, from the South Australian Research and Development Institute – Aquatic Sciences). Further updates were provided at regular (approximately monthly) face-to-face meetings with the Executive Officer and Prawn Fisheries Manager, both of whom were Co-Investigators on this project. Typically, either meeting involved planning of dates for the Nordmøre-grid trials, presentation and interpretation of results by the PI, feedback from the skipper on operational issues, and general discussion on further modification and testing of the grid. The Management Committee meetings will continue to be the forum for communicating with industry and PIRSA on further development, although both stakeholder groups are waiting on the final report before the next steps are considered.

10. Project materials developed

A manuscript for this work, entitled 'Refining a Nordmøre-grid for the Spencer Gulf penaeid-trawl fishery', has been submitted for publication in *Fisheries Management and Ecology*.

Also, a summary of the main findings were presented at: (1) a workshop for the Giant Cuttlefish Working Group on 1 September 2016 at the South Australian Aquatic Sciences Centre, West Beach; and (2) the Australian Society for Fish Biology – Oceania Chondrichthyan Society Joint Conference on 7 September 2016 in Hobart, Tasmania.

11. Appendices

Appendix 1. Project staff

Researchers:

- Craig Noell – Principal Investigator (SARDI)
- Matt Broadhurst – Co-Investigator (DPI NSW)
- Steve Kennelly – Co-Investigator (IC Independent Consulting)

Field and technical support:

- Owen Burnell (SARDI)
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- Ashley Lukin (FV 'Lunar Sea')
- Geoff Earle (FV 'Lunar Sea')
- Tom Clarke (FV 'Lunar Sea')
- Josh Redden (FV 'Lunar Sea')
- Geoff Johnson (net maker, NSW)
- Steve Everson (BRD fabricator, NSW)
- Dave Craig (net maker, SGWCPFA)

Appendix 2. Intellectual property

This report will be made freely available and can be copied and distributed provided attribution of the work is made.

Appendix 3. Supplementary data and analyses

Table A-1. Details of experiment 1, including dates, coordinates (GDA94) and distance trawled for each haul.

Date	Night	Haul	Start		Finish		Distance (km)
			Latitude	Longitude	Latitude	Longitude	
10/04/15	1	1	-33.431	137.575	-33.394	137.579	4.113
10/04/15	1	2	-33.329	137.601	-33.357	137.600	3.174
10/04/15	1	3	-33.356	137.601	-33.325	137.601	3.449
10/04/15	1	4	-33.392	137.609	-33.365	137.610	3.044
10/04/15	1	5	-33.365	137.589	-33.337	137.589	3.154
10/04/15	1	6	-33.395	137.584	-33.418	137.580	2.607
11/04/15	2	1	-33.735	137.552	-33.763	137.557	3.111
11/04/15	2	2	-33.738	137.550	-33.766	137.555	3.144
11/04/15	2	3	-33.785	137.525	-33.771	137.558	3.417
11/04/15	2	4	-33.785	137.525	-33.773	137.556	3.188
11/04/15	2	5	-33.777	137.576	-33.807	137.551	4.064
11/04/15	2	6	-33.844	137.526	-33.820	137.543	3.063
11/04/15	2	7	-33.845	137.503	-33.880	137.491	4.003
12/04/15	3	1	-33.477	137.518	-33.444	137.512	3.752
12/04/15	3	2	-33.370	137.519	-33.338	137.528	3.628
12/04/15	3	3	-33.280	137.555	-33.251	137.571	3.557
12/04/15	3	4	-33.206	137.626	-33.183	137.651	3.469
12/04/15	3	5	-33.183	137.648	-33.210	137.621	3.942
12/04/15	3	6	-33.301	137.547	-33.333	137.535	3.780
12/04/15	3	7	-33.390	137.528	-33.423	137.524	3.706
13/04/15	4	1	-33.910	137.204	-33.924	137.172	3.339
13/04/15	4	2	-33.926	137.169	-33.911	137.202	3.402
13/04/15	4	3	-33.912	137.222	-33.901	137.257	3.465
13/04/15	4	4	-33.911	137.257	-33.921	137.219	3.707
13/04/15	4	5	-33.921	137.218	-33.921	137.255	3.477
13/04/15	4	6	-33.881	137.380	-33.881	137.417	3.417
13/04/15	4	7	-33.913	137.411	-33.885	137.425	3.301

Table A-2. Details of experiment 2, including dates, coordinates (GDA94) and distance trawled for each haul.

Date	Night	Haul	Start		Finish		Distance (km)
			Latitude	Longitude	Latitude	Longitude	
07/11/15	1	1	-34.269	136.769	-34.239	136.778	3.409
07/11/15	1	2	-34.228	136.784	-34.260	136.781	3.499
07/11/15	1	3	-34.275	136.786	-34.242	136.789	3.629
07/11/15	1	4	-34.139	136.851	-34.109	136.858	3.387
07/11/15	1	5	-34.092	136.865	-34.061	136.875	3.497
07/11/15	1	6	-34.089	136.860	-34.058	136.866	3.513
08/11/15	2	1	-34.037	136.696	-34.022	136.725	3.158
08/11/15	2	2	-34.010	136.752	-33.994	136.783	3.370
08/11/15	2	3	-33.986	136.802	-33.969	136.834	3.514
08/11/15	2	4	-33.946	136.897	-33.961	136.868	3.227
08/11/15	2	5	-33.952	136.843	-33.934	136.876	3.653
08/11/15	2	6	-33.881	137.023	-33.863	137.058	3.836
09/11/15	3	1	-33.479	137.572	-33.451	137.582	3.222
09/11/15	3	2	-33.471	137.573	-33.443	137.582	3.202
09/11/15	3	3	-33.427	137.580	-33.398	137.584	3.174
09/11/15	3	4	-33.360	137.574	-33.392	137.574	3.561
09/11/15	3	5	-33.379	137.557	-33.406	137.552	3.084
09/11/15	3	6	-33.446	137.559	-33.473	137.564	3.027
10/11/15	4	1	-33.422	137.537	-33.393	137.539	3.214
10/11/15	4	2	-33.420	137.538	-33.392	137.540	3.084
10/11/15	4	3	-33.361	137.583	-33.394	137.581	3.679
10/11/15	4	4	-33.364	137.583	-33.394	137.581	3.385
10/11/15	4	5	-33.375	137.618	-33.403	137.619	3.067
10/11/15	4	6	-33.424	137.619	-33.450	137.617	2.905
11/11/15	5	1	-33.929	137.156	-33.940	137.121	3.516
11/11/15	5	2	-33.951	137.097	-33.941	137.128	3.045
11/11/15	5	3	-33.917	137.214	-33.909	137.245	3.044
11/11/15	5	4	-33.910	137.243	-33.920	137.207	3.465
11/11/15	5	5	-33.913	137.235	-33.903	137.271	3.477
11/11/15	5	6	-33.877	137.383	-33.850	137.415	4.160

Table A-3. Details of experiment 3, including dates, coordinates (GDA94) and distance trawled for each haul.

Date	Night	Haul	Start		Finish		Distance (km)
			Latitude	Longitude	Latitude	Longitude	
28/04/16	1	1	-33.211	137.620	-33.181	137.649	4.311
28/04/16	1	2	-33.151	137.702	-33.169	137.674	3.268
28/04/16	1	3	-33.104	137.740	-33.074	137.752	3.488
28/04/16	1	4	-33.044	137.767	-33.024	137.790	3.188
28/04/16	1	5	-33.007	137.823	-33.028	137.785	4.224
28/04/16	1	6	-33.096	137.744	-33.068	137.755	3.216
29/04/16	2	1	-33.208	137.631	-33.231	137.611	3.190
29/04/16	2	2	-33.253	137.584	-33.281	137.567	3.478
29/04/16	2	3	-33.317	137.552	-33.285	137.556	3.578
29/04/16	2	4	-33.255	137.581	-33.287	137.562	3.960
29/04/16	2	5	-33.286	137.551	-33.259	137.567	3.312
29/04/16	2	6	-33.250	137.578	-33.283	137.558	4.152
30/04/16	3	1	-33.327	137.542	-33.357	137.540	3.290
30/04/16	3	2	-33.391	137.534	-33.422	137.531	3.426
30/04/16	3	3	-33.418	137.539	-33.384	137.541	3.753
30/04/16	3	4	-33.422	137.531	-33.392	137.535	3.280
30/04/16	3	5	-33.417	137.525	-33.387	137.525	3.335
30/04/16	3	6	-33.393	137.532	-33.425	137.524	3.649
01/05/16	4	1	-33.840	137.512	-33.870	137.498	3.616
01/05/16	4	2	-33.908	137.466	-33.924	137.431	3.698
01/05/16	4	3	-33.897	137.462	-33.872	137.483	3.415
01/05/16	4	4	-33.921	137.482	-33.920	137.443	3.619
01/05/16	4	5	-33.917	137.416	-33.884	137.418	3.659
01/05/16	4	6	-33.857	137.448	-33.885	137.426	3.744

Table A-4. Deployment sequence for experiments 1, 2 and 3. For each paired comparison, the first configuration is the port side, and the second configuration is the starboard side. Abbreviations: C, control; A, 35-mm grid; B, 45-mm grid; D, AB-exit 75N-panel grid; E, 1N2B-exit 75N-panel grid; F, 1N2B-exit 62N-panel grid; G, 1N1B-exit 62N-panel grid; x, non-identical codend; *, additional replicates to the planned sequence.

Haul	Night 1	Night 2	Night 3	Night 4	Night 5
Experiment 1					
1	B v C	A v C	C v B	C v A*	–
2	B v A	A v B	C v A	C v A	–
3	A v C	C v B	B v A	B v A	–
4	A v B	C v A	B v C	B v C	–
5	C v B	B v A	A v C	A v C	–
6	C v A	B v C	A v B	A v B	–
7	–	B v C*	A v B*	C v B	–
Experiment 2					
1	D v E	x v D	E v x	E v C	D v C
2	x v C	C v E	C v x	D v x	x v C
3	x v D	E v D	C v D	D v E	E v D
4	C v D	E v x	E v C	x v C	E v x
5	C v E	C v x	x v D	x v E	D v x
6	E v x	D v C	D v E	C v D	C v E
Experiment 3					
1	E v F	G v E	F v G	F v C	–
2	G v C	C v F	G v C	E v G	–
3	G v E	F v E	C v E	E v F	–
4	C v E	F v G	F v C	G v C	–
5	C v F	C v G	E v G	G v F	–
6	F v G	E v C	E v F	C v E	–

Table A-5. Scientific names, common names and numbers (n) of bycatch species caught during experiments 1, 2 and 3, and, for subsampled teleosts, median and range of total lengths. Mussels were not counted, only weighed (weights are shown in *italic*). –, not caught; nr, not recorded.

Family (or next lowest taxonomic level)	Scientific name	Common name	n_1	n_2	n_3	Total length (cm)	
						Median	Range
Teleosts							
Apogonidae	*Vincentia badia*	Scarlet Cardinalfish	60	684	105	6.5	4.5–10.5
Callionymidae	*Repomucenus calcaratus*	Spotted Dragonet	1425	4392	2177	12.5	8.5–21.5
	Pseudocaranx wrighti	Skipjack Trevally	1923	19057	15457	11.5	5.5–17.5
	Trachurus declivis	Common Jack Mackerel	–	34	117	14.8	11.5–20.5
	Trachus novaezelandiae	Yellowtail Scad	61	21	–	16.0	13.0–17.5
Chaetodontidae	*Chelmonops curiosus*	Western Talma	–	–	17	11.0	9.5–12.5
	Hyperlophus vittatus	Sandy Sprat	36	53	–	8.5	7.0–10.5
	Sardinops sagax	Australian Sardine	68	141	–	12.0	6.5–14.5
Cynoglossidae	*Cynoglossus broadhursti*	Southern Tongue Sole	86	60	74	20.5	9.5–23.0
Diodontidae	*Diodon nicthemerus*	Globefish	2	8	4	nr	nr
Engraulidae	*Engraulis australis*	Australian Anchovy	183	114	38	10.5	7.0–13.0
Gempylidae	*Thyrsites atun*	Barracouta	–	72	–	28.3	27.0–29.0
Gerreidae	*Parequula melbournensis*	Silverbelly	1048	3797	965	9.5	6.0–18.0
Gobiesocidae	Not identified	Clingfish	–	21	–	9.0	8.0–10.0
Gonorynchidae	*Gonorynchus greyi*	Beaked Salmon	14	114	17	24.3	20.0–27.0
Hemiraphidae	*Hyporhamphus melanochir*	Southern Garfish	26	–	29	14.3	10.0–14.5
	Acanthaluteres spilomelanurus	Bridled Leatherjacket					
	Acanthaluteres vittiger	Toothbrush Leatherjacket					
	Brachaluteres jacksonianus	Southern Pygmy Leatherjacket					
	Eubalichthys mosaicus	Mosaic Leatherjacket					
	Scobinichthys granulatus	Rough Leatherjacket					
	Thamnaconus degeni	Bluefin Leatherjacket					
Mullidae	*Upeneichthys vlamingii*	Bluespotted Goatfish	2656	5362	1248	11.5	4.5–21.0
Odacidae	*Neoodax balteatus*	Little Weed Whiting	18	55	39	8.5	7.0–12.0
	Aracana ornata	Ornate Cowfish					
	Aracana aurita	Shaw's Cowfish					
Paralichthyidae	*Pseudorhombus jenynsii*	Smalltooth Flounder	532	251	608	18.8	14.0–37.0
Pegasidae	*Pegasus lancifer*	Sculptured Seamoth	–	47	–	7.5	7.0–8.5
Pempheridae	*Parapriacanthus elongatus*	Elongate bullseye	6204	1884	1698	8.5	5.0–11.5

Table A-5. *Continued*

Family (or next lowest taxonomic level)	Scientific name	Common name	n_1	n_2	n_3	Total length (cm)	
						Median	Range
Pentacerotidae	*Parazanclistius hutchinsi*	Short Boarfish	–	42	1	11.5	10.5–12.5
Pinguipedidae	*Parapercis haackei*	Wavy Grubfish	130	52	50	7.0	6.0–14.0
	Platycephalus aurimaculatus	Toothy Flathead					
	Platycephalus richardsoni	Tiger Flathead					
	Thysanophrys cirronasa	Tasselsnout Flathead					
	Sillaginodes punctata	King George Whiting	57	590	230	24.5	21.0–33.5
	Sillago bassensis	Southern School Whiting	–	173	–	18.0	17.0–22.5
Sparidae	*Pagrus auratus*	Snapper	–	0	20	9.5	9.5–9.5
Sphyraenidae	*Sphyraena novaehollandiae*	Snook	–	2	–	nr	nr
	Leptoichthys fistularius	Brushtail Pipefish					
	Stigmatopora nigra	Spotted Pipefish					
Terapontidae	*Pelates octolineatus*	Western Striped Grunter	323	100	463	16.0	6.0–20.0
	Polyspina piosae	Orangebarred Puffer	–	–	52	7.5	6.5–8.5
	Contusus brevicaudus	Prickly Toadfish					
	Tetractenos glaber	Smooth Toadfish					
Triglidae	*Lepidotrigla papilio*	Spiny Gurnard	572	1662	147	9.0	6.5–13.0
	Gymnapistes marmoratus	Soldier					
	Maxillicosta scabriceps	Little Gurnard Perch					
	Neosebastes bougainvilii	Gulf Gurnard Perch					
Chondrichthyans							
Callorhinchidae	*Callorhinchus milii*	Elephantfish	–	1	–	nr	nr
Dasyatidae	*Dasyatis thetidis*	Black Stingray	–	2	–	nr	nr
Heterodontidae	*Heterodontus portusjacksoni*	Port Jackson Shark	31	61	20	nr	nr
Hypnidae	*Hypnos monopterygium*	Coffin Ray	1	–	–	nr	nr
Myliobatidae	*Myliobatis tenuicaudatus*	Southern Eagle Ray	–	4	–	nr	nr
Orectolobidae	*Orectolobus maculatus*	Ornate Wobbegong	14	–	3	nr	nr
	Aptychotrema vincentiana	Western Shovelnose Ray	–	1	–	nr	nr
	Trygonorrhina dumerilii	Southern Fiddler Ray	–	3	–	nr	nr
Squatinidae	*Squatina australis*	Australian Angel Shark	–	2	2	nr	nr
Urolophidae	*Urolophus paucimaculatus*	Sparsely Spotted Stingaree	4	–	–	nr	nr
Superorder Batoidea	Not identified	Rays and skates	4	28	3	nr	nr

Table A-5. *Continued*

Family (or next lowest taxonomic level)	Scientific name	Common name	n_1	n_2	n_3	Total length (cm)	
						Median	Range
Cephalopods							
Octopodidae	*Octopus kaurna*	Southern Sand Octopus	–	17	20	nr	nr
Ommastrephidae	*Nototodarus gouldi*	Gould's Squid	–	29	–	nr	nr
Sepiadariidae	*Sepioloidea lineolata*	Striped Pyjama Squid	–	12	6	nr	nr
	Sepia apama	Giant Cuttlefish	227	15	165	nr	nr
	Sepia braggi	Slender Cuttlefish	–	1	–	nr	nr
	Sepia novaehollandiae	New Holland Cuttlefish	407	126	265	nr	nr
Crustaceans							
Carcinidae	*Nectocarcinus integrifons*	Rough Rock Crab	–	44	–	nr	nr
Majidae	Not identified	Spider crab	–	8	–	nr	nr
Penaeidae	*Metapenaeopsis* sp.	Velvet Shrimp	889	2697	344	nr	nr
	Ovalipes australiensis	Common Sand Crab	–	1240	–	nr	nr
	Portunus armatus	Blue Swimmer Crab	13107	7192	4524	nr	nr
Squillidae	*Erugosquilla grahami*	Mantis Shrimp	7	850	43	nr	nr
Bivalves							
Mytilidae	Not identified	Mussel	*29 kg*	*24 kg*	*89 kg*	nr	nr
Pectinidae	Not identified	Scallop	15	12	13	nr	nr
Pinnidae	*Pinna bicolor*	Razor Clam	–	–	3	nr	nr
Order Veneroida	Not identified	Cockle	16	16	–	nr	nr
Echinoderms							
Holothuriidae	*Holothuria hartmeyeri*	Handsome Sea Cucumber	1	5	–	nr	nr
Class Asteroidea	Not identified	Starfish	–	2	2	nr	nr
Class Echinoidea	Not identified	Sea urchin	–	16	5	nr	nr

Table A-6. Linear mixed model Wald *F*-values (**$p < 0.01$) for the fixed effect of experiment (control codends only) on mean individual weights of key species, predicted means (in grams, ± SE), and significant ($p < 0.05$) false-discovery-rate (FDR)-adjusted paired comparisons. Abbreviation: –, no significant paired comparison.

Variable	Wald *F*	Predicted means (± SE)			FDR
		Experiment 1	Experiment 2	Experiment 3	
Mean individual wt of Blue Swimmer Crabs	5.49**	100.05 ± 11.51	147.08 ± 12.41	136.01 ± 13.21	E1 < E2
Mean individual wt of Giant Cuttlefish	6.17**	432.44 ± 36.69	157.00 ± 84.74	489.44 ± 42.37	E1 = E3 > E2
Mean individual wt of New Holland Cuttlefish	0.54	102.05 ± 12.46	94.01 ± 15.25	83.63 ± 14.62	–

Table A-7. Linear mixed model Wald *F*-values (**$p < 0.01$) for the fixed effect of trawl configuration on mean individual weights of key species from experiment 1, predicted means (in grams, ± SE), and significant ($p < 0.05$) false-discovery-rate (FDR)-adjusted paired comparisons. Abbreviations: A, 35-mm grid; B, 45-mm grid; C, control; –, no significant paired comparison.

Variable	Wald *F*	Predicted means (± SE)			FDR
		A	B	Control	
Mean individual wt of Blue Swimmer Crabs	3.14	86.64 ± 13.62	84.64 ± 13.58	99.08 ± 13.62	–
Mean individual wt of Giant Cuttlefish	8.14**	271.79 ± 40.69	293.83 ± 40.03	427.80 ± 40.04	A = B < C
Mean individual wt of New Holland Cuttlefish	2.51	77.93 ± 12.35	80.97 ± 12.01	102.21 ± 12.33	–

Table A-8. Linear mixed model Wald *F*-values (*$p < 0.05$) for the fixed effect of trawl configuration on mean individual weights of key species from experiment 2, predicted means (in grams, ± SE), and significant ($p < 0.05$) false-discovery-rate (FDR)-adjusted paired comparisons. Abbreviations: D, AB-exit 75N-panel grid; E, 1N2B-exit 75N-panel grid; †, insufficient data for analysis; –, no significant paired comparison.

Variable	Wald *F*	Predicted means (± SE)			FDR
		D	E	Control	
Mean individual wt of Blue Swimmer Crabs	4.00*	119.93 ± 20.73	114.55 ± 20.35	142.61 ± 20.15	–
Mean individual wt of Giant Cuttlefish	†	142.84 ± 79.22	225.96 ± 51.82	115.96 ± 51.82	–
Mean individual wt of New Holland Cuttlefish	0.10	92.92 ± 8.55	88.12 ± 10.47	94.01 ± 9.37	–

Table A-9. Linear mixed model Wald *F*-values (*$p < 0.05$; ***$p < 0.001$) for the fixed effect of trawl configuration on mean individual weights of key species from experiment 3, predicted means (in grams, ± SE), and significant ($p < 0.05$) false-discovery-rate (FDR)-adjusted paired comparisons. Abbreviations: E, 1N2B-exit 75N-panel grid; F, 1N2B-exit 62N-panel grid; G, 1N1B-exit 62N-panel grid; C, control; –, no significant paired comparison.

Variable	Wald *F*	Predicted means (± SE)				FDR
		E	F	G	Control	
Mean individual wt of Blue Swimmer Crabs	11.22***	89.58 ± 9.96	99.71 ± 9.74	95.26 ± 9.96	137.55 ± 9.74	E = F = G < C
Mean individual wt of Giant Cuttlefish	3.64*	298.16 ± 66.36	360.97 ± 59.07	256.62 ± 63.50	489.44 ± 59.07	–
Mean individual wt of New Holland Cuttlefish	0.09	79.08 ± 6.63	82.71 ± 6.35	82.99 ± 6.95	83.35 ± 6.63	–

Table A-10. Linear mixed model Wald *F*-values (**$p < 0.01$; ***$p < 0.001$) for the fixed effect of trawl configuration on log-transformed catches from experiment 1, predicted means (kilograms and numbers per 30-min deployment), and significant ($p < 0.05$) false-discovery-rate (FDR)-adjusted paired comparisons. Western King Prawn industry categories are counts per pound (454 g). U8 and U10, under 8 or 10 prawns per pound, respectively. Abbreviations: A, 35-mm grid; B, 45-mm grid; C, control; –, no significant paired comparison.

Variable	Wald *F*	Predicted means			FDR
		A	B	Control	
Retained catches					
Wt of Western King Prawns					
U8	0.20	1.15	1.21	1.19	–
U10	0.74	3.66	3.86	3.31	–
10–15	0.93	11.95	12.39	12.94	–
16–20	0.44	42.80	44.59	43.84	–
21–30	0.52	33.47	34.65	36.07	–
31–40	0.17	10.23	10.59	10.44	–
Soft and broken	2.76	2.91	2.78	3.48	–
Total	0.61	73.77	76.44	76.54	–
By-product					
Wt of Southern Calamari	0.11	2.27	2.27	2.36	–
Wt of Balmain Bugs	11.64***	0.03	0.05	0.25	A = B < C
Discarded catches					
Key invertebrates					
No. of Blue Swimmer Crabs	16.14***	182.59	244.49	489.74	A = B < C
Wt of Blue Swimmer Crabs	27.67***	14.14	18.80	42.86	A = B < C
Mean individual wt of Blue Swimmer Crabs	3.14	86.64	84.64	99.08	–
No. of Giant Cuttlefish	5.86**	2.98	4.40	6.78	A < C
Wt of Giant Cuttlefish	12.41***	0.82	1.46	3.07	A = B < C
Mean individual wt of Giant Cuttlefish	8.14**	271.79	293.83	427.80	A = B < C
No. of New Holland Cuttlefish	1.21	8.74	9.94	7.53	–
Wt of New Holland Cuttlefish	0.42	0.71	0.82	0.71	–
Mean individual wt of New Holland Cuttlefish	2.51	77.93	80.97	102.21	–
Most abundant teleosts (rank 1–6)					
No. of monacanthids	0.62	268.48	305.84	238.02	–
No. of Skipjack Trevally	0.45	63.29	86.63	56.32	–
No. of Elongate Bullseye	0.31	104.93	127.12	113.02	–
No. of Bluespotted Goatfish	0.05	70.04	77.38	83.02	–
No. of Spotted Dragonet	1.06	24.00	37.77	28.10	–
No. of Silverbelly	1.33	26.09	36.44	18.52	–
Main taxonomic groups					
No. of elasmobranchs	18.78***	0.26	0.28	2.27	A = B < C
Wt of elasmobranchs	29.24***	0.17	0.12	3.95	A = B < C
Wt of porifera	28.40***	1.88	2.36	21.42	A = B < C
Wt of algae and seagrasses	0.34	2.38	2.54	2.88	–
Wt of teleosts	1.11	12.27	16.23	15.75	–
Total bycatch					
Wt of total bycatch	40.61***	30.65	38.28	79.39	A = B < C

Table A-11. Linear mixed model Wald *F*-values (**p* < 0.05; ***p* < 0.01; ****p* < 0.001) for the fixed effect of trawl configuration on log-transformed catches from experiment 2, predicted means (kilograms and numbers per 30-min deployment), and significant (*p* < 0.05) false-discovery-rate (FDR)-adjusted paired comparisons. Western King Prawn industry categories are counts per pound (454 g). U8 and U10, under 8 or 10 prawns per pound, respectively. Abbreviations: D, AB-exit 75N-panel grid; E, 1N2B-exit 75N-panel grid; C, control; †, insufficient data for analysis; –, no significant paired comparison.

Variable	Wald *F*	Predicted means			FDR
		D	E	Control	
Retained catches					
Wt of Western King Prawns					
U8	0.04	1.41	1.47	1.42	–
U10	0.00	1.52	1.52	1.51	–
10–15	2.25	6.63	5.87	7.28	–
16–20	1.36	11.65	9.75	10.79	–
21–30	3.69	8.98	7.38	8.69	–
31–40	0.71	0.73	0.60	0.66	–
Soft and broken	5.14*	1.26	1.47	2.27	D < C
Total	2.73	28.80	25.79	29.89	–
By-product					
Wt of Southern Calamari	0.52	0.70	0.95	0.90	–
Wt of Balmain Bugs	1.70	0.07	0.05	0.12	–
Discarded catches					
Key invertebrates					
No. of Blue Swimmer Crabs	14.76***	127.08	136.29	256.60	D = E < C
Wt of Blue Swimmer Crabs	15.74***	10.32	11.40	31.11	D = E < C
Mean individual wt of Blue Swimmer Crabs	4.00*	119.93	114.55	142.61	–
No. of Giant Cuttlefish	0.09	0.29	0.36	0.29	–
Wt of Giant Cuttlefish	0.20	0.04	0.05	0.04	–
Mean individual wt of Giant Cuttlefish	†	142.84	225.96	115.96	–
No. of New Holland Cuttlefish	3.04	3.65	2.45	2.76	–
Wt of New Holland Cuttlefish	3.14	0.45	0.24	0.30	–
Mean individual wt of New Holland Cuttlefish	0.10	92.92	88.12	94.01	–
Most abundant teleosts (rank 1–6)					
No. of monacanthids	0.73	458.30	538.87	621.56	–
No. of Skipjack Trevally	4.74*	632.38	262.40	409.11	D > E
No. of Elongate Bullseye	1.26	41.94	56.99	28.31	–
No. of Bluespotted Goatfish	0.11	137.46	134.52	119.83	–
No. of Spotted Dragonet	1.62	120.49	81.49	112.09	–
No. of Silverbelly	0.06	95.04	91.55	106.47	–
Main taxonomic groups					
No. of elasmobranchs	7.07**	1.24	0.79	3.15	D = E < C
Wt of elasmobranchs	60.86***	0.15	0.14	7.57	D = E < C
Wt of porifera	10.50***	2.07	1.72	23.77	D = E < C
Wt of algae and seagrasses	2.07	1.34	1.53	3.01	–
Wt of teleosts	0.78	35.88	30.74	40.45	–
Total bycatch					
Wt of total bycatch	42.89***	50.34	40.85	108.34	D = E < C

Table A-12. Linear mixed model Wald *F*-values (*$p < 0.05$; **$p < 0.01$; ***$p < 0.001$) for the fixed effect of trawl configuration on log-transformed catches from experiment 3, predicted means (kilograms and numbers per 30-min deployment), and significant ($p < 0.05$) false-discovery-rate (FDR)-adjusted paired comparisons. Western King Prawn industry categories are counts per pound (454 g). U8 and U10, under 8 or 10 prawns per pound, respectively. Abbreviations: E, 1N2B-exit 75N-panel grid; F, 1N2B-exit 62N-panel grid; G, 1N1B-exit 62N-panel grid; C, control; –, no significant paired comparison.

Variable	Wald *F*	Predicted means				FDR
		E	F	G	Control	
Retained catches						
Wt of Western King Prawns						
U8	0.77	0.34	0.37	0.35	0.35	–
U10	3.15*	0.88	1.00	1.29	0.72	–
10–15	0.71	9.57	10.27	9.92	9.04	–
16–20	1.16	22.06	25.00	22.52	22.78	–
21–30	1.05	28.32	31.53	31.44	31.33	–
31–40	1.24	13.08	13.62	14.56	14.52	–
Soft and broken	5.45**	4.48	3.97	4.03	6.00	F = G < C
Total	1.03	58.93	65.73	62.18	62.79	–
By-product						
Wt of Southern Calamari	0.26	3.75	3.61	3.39	3.76	–
Wt of Balmain Bugs	30.85***	0.07	0.02	0.02	0.56	E = F = G < C
Discarded catches						
Key invertebrates						
No. of Blue Swimmer Crabs	17.59***	84.21	38.19	56.62	249.34	F < E < C; G < C
Wt of Blue Swimmer Crabs	33.00***	6.54	3.33	4.70	30.32	F < E < C; G < C
Mean individual wt of Blue Swimmer Crabs	11.22***	89.58	99.71	95.26	137.55	E = F = G < C
No. of Giant Cuttlefish	21.35***	1.65	2.15	2.00	8.49	E = F = G < C
Wt of Giant Cuttlefish	20.08***	0.52	0.84	0.56	5.26	E = F = G < C
Mean individual wt of Giant Cuttlefish	3.64*	298.16	360.97	256.62	489.44	–
No. of New Holland Cuttlefish	1.51	7.29	6.61	4.87	6.23	–
Wt of New Holland Cuttlefish	0.99	0.58	0.59	0.40	0.49	–
Mean individual wt of New Holland Cuttlefish	0.09	79.08	82.71	82.99	83.35	–
Most abundant teleosts (rank 1–6)						
No. of monacanthids	0.18	253.82	230.40	229.75	281.83	–
No. of Skipjack Trevally	0.74	237.71	296.52	227.94	200.41	–
No. of Elongate Bullseye	0.60	72.23	59.69	73.56	36.65	–
No. of Bluespotted Goatfish	2.74	57.38	38.88	68.27	22.05	–
No. of Spotted Dragonet	1.68	208.83	162.02	199.33	134.61	–
No. of Silverbelly	2.13	33.49	33.75	26.93	10.95	–
Main taxonomic groups						
No. of elasmobranchs	95.28***	0.02	0.08	0.02	1.93	E = F = G < C
Wt of elasmobranchs	171.60***	0.01	0.02	0.01	4.01	E = F = G < C
Wt of porifera	37.47***	0.42	0.34	0.39	20.40	E = F = G < C
Wt of algae and seagrasses	1.29	0.15	0.17	0.21	0.22	–
Wt of teleosts	0.12	16.16	17.29	16.02	18.32	–
Total bycatch						
Wt of total bycatch	48.73***	23.62	21.24	19.26	93.37	E = F = G < C

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