# Reducing the environmental impacts and improving the profitability of prawn trawling through a structured framework of anterior gear modifications

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**January 2016**

FRDC Project No **2011/010**

ISBN **981-1-74256-880-5**

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**2015**

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# Acknowledgments

This study was funded by the NSW Department of Primary Industries and the Fisheries Research and Development Corporation. The work would not have been possible without the considerable support and expertise of commercial fishers throughout NSW, including Donald, Brian and Geoff Johnson, Steve Everson, Graeme Williams, Donald Anderson, Malcolm Kerr and Robert Toyer.

Thanks are extended to our various co-authors, including Brian Cullis, Steve Kennelly, Greg Skilleter, Cheslav Balash, Matthew McHugh and Russell Millar for their extensive contributions to the various papers that summarise the main outcomes of the project. In particular, Russell and Matthew are applauded for their dedication to prompt analyses and writing, respectively.

We would also like to extend gratitude to other colleagues including Chris Barnes, Jen Marshall, Mitch Burns, Nick Sarapuk, Liz Hanna, Matthew Harrison, and Shiori Naka for their advice and assistance throughout the project. Finally, a large component of the field work and therefore the project would not have been possible without the commitment of Craig Brand.

# Executive summary

## Concept

This project is among the first of its kind for any Australian fishery, and indeed for any prawn (or shrimp) fishery worldwide. The work represents a four-year (from September 2011) collaborative effort between the New South Wales (NSW) fishing industry and the NSW Department of Primary Industries, Sterling Trawl Gear Services and the Australian Maritime College. This collaboration ultimately sought to provide a first step towards developing applied technological solutions to holistically mitigate key sustainability issues facing prawn-trawl fisheries. The holistic environment was achieved by adopting an eco-efficiency approach to the assessment of issues. The work mostly was concentrated in NSW, but the results have national and international application.

## Background

Globally, prawn-trawl fisheries are considered problematic in terms of environmental impacts and are characterised by a range of sustainability issues beyond the management of their target species; most of which can be separated into three broad categories. First, is the inherent imprecise size and species selection (owing to the necessary use of small mesh sizes to retain the targeted prawns) of conventional gears, with nearly all catching large unwanted organisms, collectively termed 'bycatch', that are subsequently discarded at sea (often dead). Second, is a growing socio-economic impetus for improved energy efficiency; attributable to the rising cost of fossil fuels and awareness of the need to reduce carbon emissions. Third are concerns over the potential impacts of long-term mechanical interactions of prawn trawls on the seabed and damage to some benthic habitats. The ongoing viability of prawn trawling in the 21st century requires coherent, technological solutions to key problems within these three areas.

Owing to the visual impact of large quantities of discarded bycatch, the greater majority of the research done to date has been limited to addressing the first category above, and more specifically, reducing unwanted mortalities by modifying the posterior sections (i.e. the codend) of trawls to include bycatch reduction devices (BRDs). While many BRDs have improved selectivity, none are 100% effective, with some achieving >70% reductions in total bycatches, although most by ~50%. Further, because BRDs offer few immediate benefits to fishers, there have been issues associated with their adoption.

Much less research has been done to address the remaining two broad (but inter-related) sustainability concerns associated with the high energy intensity and benthic impacts of prawn trawls. Technological solutions to both of these problems are best applied to the anterior sections of trawls, including their otter boards, ground gear, rigging configurations, designs and materials. Also, because these components ultimately determine the quantity and type of organisms that are caught by trawls, in many cases, their modification should further improve species and size selection. Equally important, such modifications should also directly benefit fishers (in terms of fuel efficiency) and so their adoption might be more easily achieved than conventional, posterior BRDs.

Some previous work has demonstrated the utility of simple (and often novel) changes to the anterior sections of trawls for reducing some impacts, but this work has involved fairly isolated experiments and usually only one of the three stated sustainability issues. Like for developing effective BRDs, there needs to be clear assessment of what might be achievable (in terms of addressing the three stated issues above) as a first step towards prioritising ongoing research and development by gear technologists and industry.

## Aims and objectives

Considering the above, the aims of this four-year project were to:

(1) identify anterior gear modifications that reduce the bycatch, fuel consumption and habitat impacts of prawn trawls, while maintaining target catches, and isolate their mechanisms of action;

(2) using this information, provide a framework and direction for the future refinement of Australian prawn trawls; and

(3) investigate the practicality of simple, but appropriate changes identified above under commercial conditions in NSW, and assist this state's fishers and managers in their implementation, adoption and where appropriate, eventual legislation.

Ultimately, the collective objective of the work was to provide clear direction for ongoing strategic fishing-gear research to improve the social and economic benefits of Australian prawn-trawl fisheries, while reducing their environmental footprint.

## Methods

The project was done using a phased approach. Following industry promotion and consultation, the first phase of experimental work involved manipulative experiments to investigate questions about the utility of various anterior configurations and modifications to address the three key sustainability categories outlined above, and was done over 30 months using NSW estuarine trawlers. These vessels catch numerous organisms across various bottom types and habitats, are rarely constrained by weather, and can be rigged to tow any established or proposed system/configuration during day or night.

The work followed a broad protocol of estimating what was achievable within the limits of established modifications. Such an approach required testing beyond what might be intuitively appropriate, so that the range of impacts could be established. In addition to identifying what might be achievable using established technologies, we also examined alternate and often quite novel ideas. The utility of various categories of modifications within this general approach were evaluated according to hierarchal criteria, involving (1) complexity/practicality, (2) maintaining target catches, and reducing (3) bycatch (including habitat impacts) and (4) drag/fuel usage.

During our first experiments, we assessed the relative performance of the various trawl systems, including single-, double-, dual-, triple-, and quad-rigged otter trawls and single- and double-beam trawls. Other manipulative experiments were then done to assess conventional and novel otter boards, netting panels, ground gears and rigging arrangements to reduce drag and improve selectivity, and also retroactively fitted modifications to reduce unwanted fish from entering trawls (including a new modification we termed the 'simple anterior fish excluder'—SAFE).

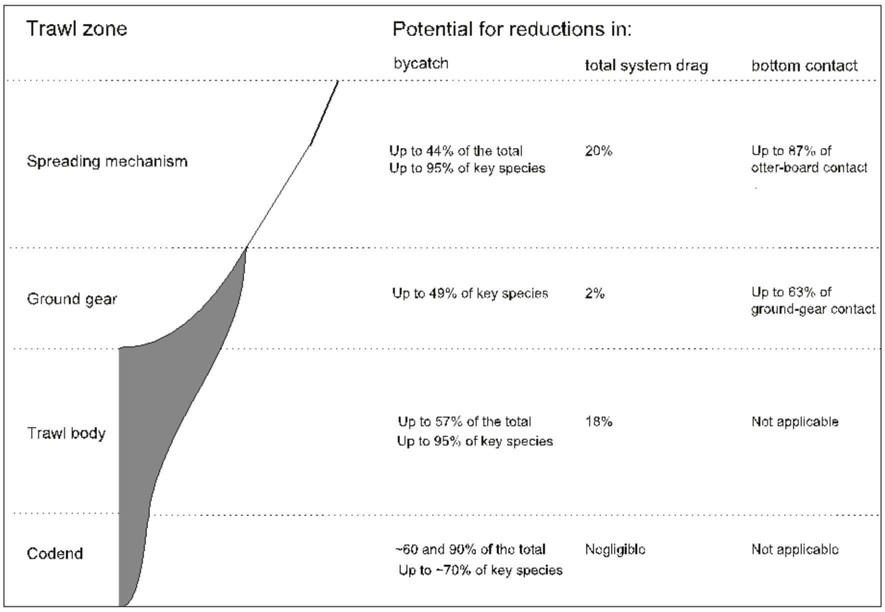
After assessment using small-scale gears, modifications were prioritised for their utility in addressing the key project objectives in consultation with a project committee. Selected, refined configurations were tested and compared against conventional configurations on board oceanic trawlers during the second experimental phase. Within this second phase, we also assessed a new trawl developed as part of the ancillary FRDC project (2011/209: Optimising a novel prawn trawl design for minimum drag and maximum eco-efficiency).

Throughout both phases, we sought to follow transparent (i.e. ratified by industry) experimental designs and with prompt publication and extension of results. This approach provided clear direction for sequential work within each phase, and now supports a coherent framework for ongoing collaborative research by gear technologists and industry, and ultimately extension and adoption.

# Results

The project identified that the anterior section of prawn trawls can be modified to maintain target catches, while dramatically reducing either unwanted bycatches by up to 95% for key species or the seabed contact of ground gear and otter boards by up to ~60 and 85% (compared to existing conventional gears), and also reduce drag (and therefore improving fuel efficiency) by up to 20%. In fact, some of the identified modifications reduced the bycatches of key species at absolute percentages equal to, or exceeding, those observed for established BRDs. But, unlike BRDs, most of the modifications assessed in this project should provide incentives for use in fisheries owing to their significant drag reductions (and improvements to efficiencies).

The results can be summarised according to modifications among three broad anterior zones, including the (1) spreading mechanism (warps, bridles, otter boards, sleds and other attachments like SAFEs), (2) ground gear (to minimise bottom contact) and (3) trawl body (mesh size, net length, hanging ratio, and mesh orientation). The figure below encapsulates these zones and the potential cumulative reductions in the three variables of interest. Previously collected information for BRDs in codends is provided as a reference (percentage bycatch reductions are assumed absolutes estimates).




Among spreading mechanisms, we showed that for a single trawl, using a beam is by far the most effective strategy in terms of simultaneously mitigating bycatch, drag and bottom contact. For otter trawls, it was clear that environmental performance broadly improved with an increasing number of nets in the system and/or fewer otter boards. Specifically, compared to a single rig, triple- and quad-rigs caught less bycatch (by up to 44%) and with lower drag (by 11%) and much less heavy otter-board contact (by 54%).

Within any otter-trawl system, reducing the otter-board angle of attack (AOA) to ~20$^{o}$ further minimised environmental impacts, with one efficient modification being the batwing otter board, which reduced drag and bottom contact by 18 and 84%, while maintaining the same spreading force as conventional designs. In terms of conventional otter boards, we showed that a retroactively fitted modification comprising a wire or line attached between the otter boards (SAFE) could potentially optimise AOA, while at the same time reduce the bycatch of unwanted fish by up to 40%. More research is required to maximise the combined outcomes of the SAFE concept.

Modifications to ground gear were also shown to effectively reduce bottom contact, while maintaining target catches at existing levels. Specifically we tested four ground gears, including a suspended configuration (termed the 'soft brush'). While drag differences were minimal, the soft brush had 63% less bottom contact than conventional ground gears, but the associated trawls still caught the same quantity of Eastern School Prawns. Within existing chain ground gears, reducing the size of chain had a positive effect on the exclusion of one bycatch species (Forktail Catfish; by 49%).

For the trawl body, we identified that the greatest potential for reducing environmental impacts (restricted to bycatch and drag) involved minimising twine area while maintaining optimal lateral mesh openings for the target species. One of the simplest approaches within conventional systems is to identify the most appropriate mesh size, and then steepen the side taper and reduce wing height—effectively shortening the trawl. Such modifications reduced drag by up to 18% and the total bycatches of fish and key species by up to 57 and 95%, respectively without affecting catches of commercial-sized prawns. Further, within a shorter trawl body, orientating wing meshes on the bar significantly reduced the unwanted catches of sub-commercial prawns by up to 72%. Other areas of the trawl warrant examination for similar utility.

## Implications

This project facilitates prioritising modifications to the configurations, otter boards, ground gear and materials of prawn trawls that maintain target catches while reducing bycatch, inefficiencies and habitat impacts. These results provide a robust base from which scientists and industry can now focus future efforts on what can be collectively termed 'Low Impact and Fuel Efficient' (LIFE) trawling systems.

Further, because some immediate solutions have been identified (especially for NSW prawn-trawl fisheries; and including beam trawls and/or multi-rigged otter trawls with smaller mesh sizes, shorter bodies and SAFEs in estuaries and alternative otter boards and ground gears in all fisheries), fisheries managers and management advisory committees should be able to use the information to design and apply appropriate industry-development programs in some fisheries. Recognising and refining such gear-based solutions will have significant long-term benefits to the trawling industry and all users of resources impacted by prawn-trawling operations.

Although not an original objective of the project, an ancillary implication of the research is the need to carefully assess benthic otter trawls used for survey work. We identified that even subtle variations (e.g. due to depth fished, warp length deployed, and towing speed) in the horizontal opening of the trawl relative to its stretched width (spread ratio or SR) can confound selectivity and therefore standardised catches. Unless SR is standardised in trawl surveys, there is a real potential for incorrect indices of relative abundances.

## Recommendations

Some of the modifications tested during this study could be immediately applied or adopted in local fisheries, including triple- or quad-rigs instead of single- and double-rigs, hydrodynamic otter boards (like the batwing), variations of the soft-brush ground gear and the shortest possible trawl bodies. However, an important outcome of the project is identification of the two key components of trawls shown to have the most potential for addressing their environmental impacts: the spreading mechanism and trawl body. Based on these results we recommend a clear need to (1) develop and refine additional innovative, high-priority technological modifications to these components that mitigate sustainability issues and (2) promote their adoption among industries through dedicated extension activities.

Within 1 above, there is a need to refine and test variations of the SAFE (e.g. possibly employing light as a stimulant) across multi-trawl systems (including different attachment points and rigging), retroactively fitted modifications to conventional otter boards to reduce AOA, alternate spreading mechanisms (e.g. winged beams), trawl designs that redistribute load to require less spreading force and with optimal twine areas, strategic panels of optimal lateral-mesh openings to improve selectivity, and new ground gear systems that have a softer interaction with the seabed (possibly employing electricity as a contact-free stimulant). Ratified designs then need to be tested across fleets to encourage adoption and refinement. Ultimately, this work will contribute towards improving the social licence and economic return of local prawn-trawl fisheries, while helping to ensure their ongoing sustainability.

## Keywords

Bycatch, Bycatch reduction devices, Bottom contact, Drag, Fish excluder, Fuel reduction, Habitat impacts, Penaeids, Trawling

# Introduction

## Background

Prawn-trawl fisheries around the world are faced with a plethora of sustainability issues beyond the management of their targeted species; most of which can be separated into three broad categories. First, of long-standing concern is the inherent poor selectivity of conventional trawls, with nearly all retaining disproportionately large ratios of incidental (collectively termed 'bycatch') to targeted catches (Andrew and Pepperell, 1992; Kelleher, 2005). Specifically, despite accounting for <1.5% of the annual global wild marine harvest, prawn-trawl fisheries contribute 25% of global bycatch (Kelleher, 2005).

Second, and ancillary to the obvious implications that the mortality of large quantities of bycatch has on stocks and the subsequent cascading responses throughout the food web, are concerns over the unseen mechanical impacts of trawls (Burridge et al., 2006). Key trawl components (e.g. the 'spreading mechanisms' and ground gear; Fig. 1) need to be sufficiently heavy to maintain bottom contact and stimulate the upward movement of benthic-orientated prawns to enable their capture. There is a concern that such contact may negatively affect non-target organisms and substrate structure across some sensitive habitats.

Third, there is a more recent but growing economic impetus for improved energy efficiencies; attributable to the rising cost of fossil fuels and awareness of the need to reduce carbon emissions (Tyedmers et al., 2005). Prawn trawls require small meshes (typically 30−50 mm stretched mesh opening−SMO; Vendeville, 1990) made from sufficiently durable twine, which translates to considerable twine-surface area, drag and therefore high energy intensity. The ongoing viability of prawn trawling into the 21st century requires a coherent, multi-faceted technological approach towards solving the key issues within the above three areas.

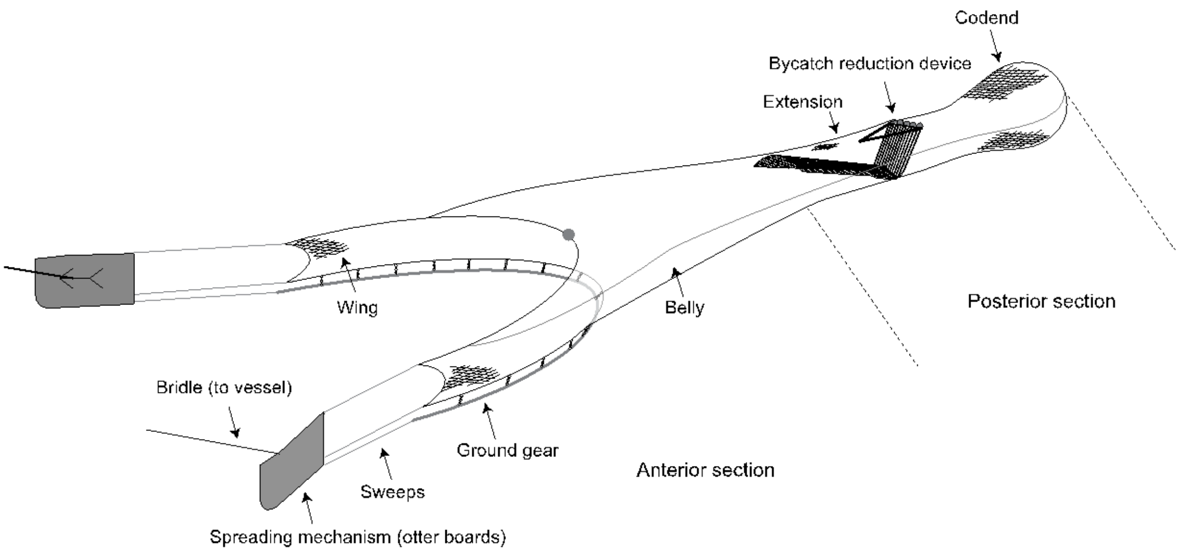



**Figure 1**. A generic prawn trawl, with the various components identified.

Owing to the visual impacts of large quantities of discarded bycatch, the majority of research done to date has concentrated on addressing the first category above, and more specifically, mitigating unaccounted fishing mortalities through improved species and size selection and, to a lesser extent, changes to fishing operations (Broadhurst et al., 2006). A large percentage of the global effort in this area originates from Australia (reviewed by Broadhurst, 2000), and has mostly involved modifying the posterior sections of trawls (i.e. the codend, extension and aft belly; Fig. 1) to include physical bycatch reduction devices (BRDs) designed to separate target and incidental organisms based on either their size or behaviour (Andrew et al., 1993; Robins-Troeger, 1995; Brewer et al., 1998; Courtney et al., 2006; Broadhurst et al., 2011).

While many BRDs have improved the selectivity of prawn trawls, none are 100% effective, with total bycatch reductions nearly always <70% and mostly around 30−50% (Broadhurst, 2000). More recently, for some Australian fisheries, mortalities to the remaining discards have been further mitigated via changes to on board handling practices. However, a suite of environmental, technical and biological factors restrict the utility of such changes (in terms of actually reducing discard mortality) to inshore and estuarine, small-scale operations and preclude their application in many offshore fisheries (Broadhurst et al., 2006).

Much less research has been done to address the remaining two broad (but inter-related) sustainability concerns associated with the benthic impacts of prawn trawls and/or their operational energy intensity (but see Sumpton et al., 1989). It is clear, however, that holistic technological solutions to concomitantly address both categories of problems will require ongoing changes to the anterior sections of trawls, including the spreading mechanisms (e.g. warps, bridles, otter boards, sleds and sweeps), ground gears, rigging configurations, body designs and netting materials (Sterling and Eayrs, 2010; Fig. 1). Further, because the components within this area of trawling systems ultimately determine the quantity and type of organisms that enter the codend, in many cases, it should be feasible to structure individual modifications to address all three sustainability issues above, including incrementally improving species and size selection.

There is sufficient evidence to demonstrate the utility of simple changes to the anterior sections of trawls for reducing some impacts (e.g. Sumpton et al., 1989; Conolly, 1992; Broadhurst et al., 2000), but there has not been any attempt at a coherent framework for identifying and then progressing modifications beyond isolated experiments. As was demonstrated during the development of effective BRDs in codends in NSW, there needs to be clear delineation of what might be achievable for any particular suite of changes, followed by adequate comprehension of the key underlying mechanisms of influence (discussed by Broadhurst et al., 2007). Such an approach is an imperative step towards prioritising ongoing strategic research and development by government agencies and industries.

Considering the above, this project did not seek to examine any one particular modification to the anterior sections of prawn trawls. Rather, through applied work in NSW prawn-trawl fisheries, we sought to provide the required framework for progressing future national (and international) research, and a holistic approach to developing effective technological changes to prawn-trawl systems that reduce their overall environmental impacts and improve their economic and social outcomes. To achieve this goal, we aimed to follow a simple, but coherent protocol involving:

(1) quantifying and publishing the range, relative utility and mechanisms of impacts for established and novel technological modifications that address the stated problems; and then

(2) based on the available data, provide a clear direction for future scientific research and concomitant industry development of appropriate solutions.

## Need

In Australia, more than 1100 vessels are endorsed to target 12 key prawn species off all coastal states and territories except Tasmania, for an estimated total catch of ~21 000 t worth ~274 million A$ (ABARES, 2015). Australian prawn trawlers range between ~8−25 m, and tow various trawl systems comprising different mesh sizes and rigging; the application and/or legislation of which (in many cases) are based on either the preferential use of particular arrangements that were in place when that fishery's legislation was established or, more recently, unsubstantiated perceptions about how the legislated gear suited the prevailing management priorities.

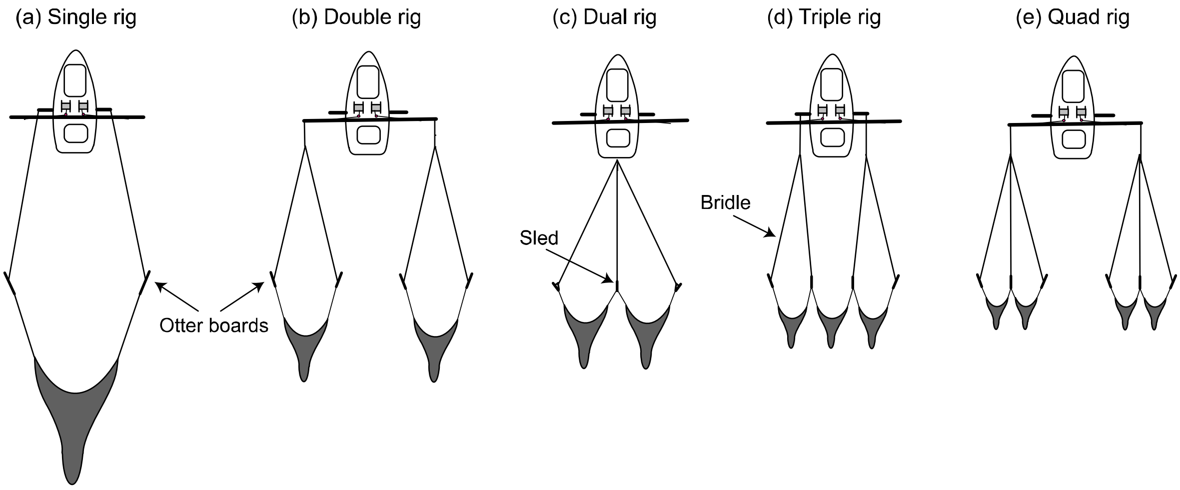



**Figure 2.** Representation of (a) single-, (b) double-, (c) dual-, (d) triple- and (e) quad-rigs used in Australia.

Notwithstanding considerable diversity, virtually all trawl designs are deployed within one of five general anterior configurations (Fig. 2). The traditional, albeit antiquated, prawn-trawling system involves a single trawl spread by either two otter boards or a beam (Figs 1, 2a and 3). While some small vessels working in rivers and estuaries in Queensland and NSW still tow single trawls, this method was superseded among most larger oceanic vessels throughout Australia by multi-trawl configurations (double rig in the 70s and higher-order systems in the early 80s), which offer sequential (albeit unsubstantiated in most cases) reductions in drag for the same horizontal opening, facilitated by lower twine and otter-board areas (Sterling and Eayrs, 2010).

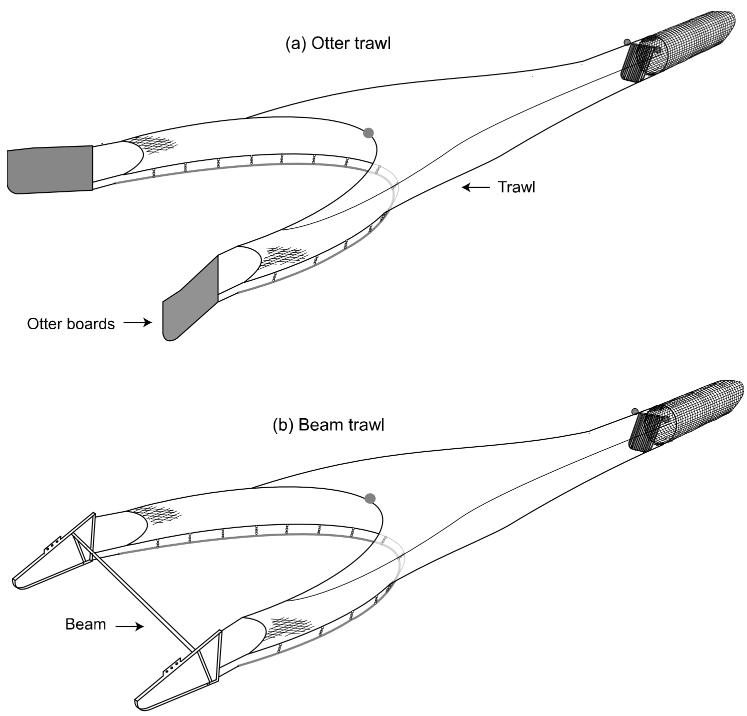



**Figure 3.** Single-rigged (a) otter and (b) beam trawls.

Among multi-trawl systems, and like most of the world's prawn-trawling fleets, 'twin' or 'double' rig is a common Australian configuration involving two trawls; each with independent otter boards and bridles and towed from outriggers on each side of the vessel (Figs 2b and 3). Another version of paired trawls, which is no longer widely used, is 'dual rig' whereby the two trawls are connected at a centre sled, spread by only one pair of otter boards, and towed from the centre-line of the vessel (Fig. 2c).

'Triple rig' is used in the deeper fishing grounds off QLD and NSW and, like single- and dual-rig, comprises only two otter boards to spread the entire configuration, but the three trawls are connected wing-to-wing at two sleds and associated bridles (Fig. 2d). In many cases, the centre trawl is slightly larger than the two outside trawls.

'Quad rig' is the last configuration and essentially comprises a set of dual rig towed from outriggers on each side of the vessel (like double rig) (Fig. 2e). Quad rig currently is restricted to vessels working in the northern half of Australia, but is a common choice where permitted by operators that choose to fish predominantly shallow water (<50 m).

Irrespective of the trawl configuration, considerable effort has been directed towards reducing unwanted bycatches via posterior modifications (BRDs in codends) in most Australia prawn-trawl fisheries (Andrew et al., 1993; Robins-Troeger, 1995; Brewer et al., 1998; Courtney et al., 2006; Broadhurst et al., 1996; 2002; 2004; 2011; Fig. 1). By comparison, very little science has been done anywhere to assess changes to anterior prawn-trawl configurations, despite the acknowledgement of clear differences in drag (and therefore efficiencies) and preliminary evidence of variations in size and species selectivity and habitat impacts (Sumpton et al., 1989; Broadhurst et al., 2000). It is highly likely that, within the current range of anterior-trawl configurations used in Australia, there exist optimal combinations, with particular spreading mechanisms, ground gears, and netting materials that could significantly address the key sustainability issues common among all benthic-trawl fisheries.

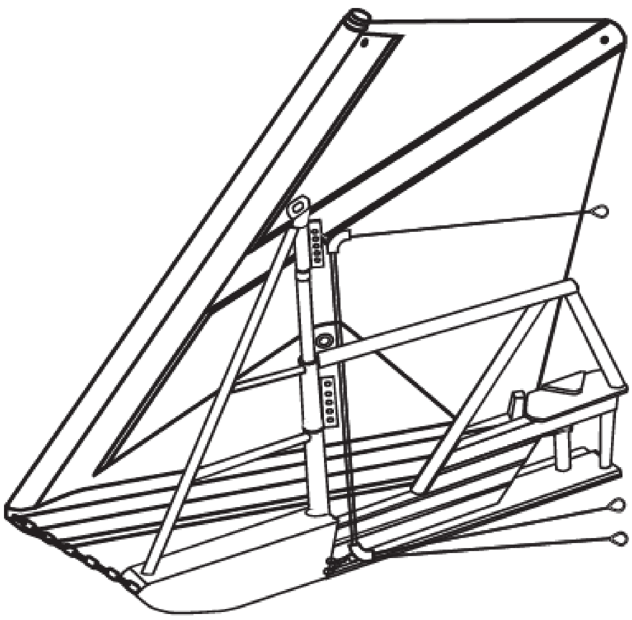


**Figure 4.** A batwing otter board.

Beyond conventional trawl systems are new, potentially more efficient and lower impacting components, including hydrodynamically refined otter boards such as the 'batwing' (Fig. 4), or novel alterations to existing designs that reduce their impacts (e.g. Kennelly and Broadhurst, 2002). Such research is still in its infancy, but nevertheless important because otter boards are likely to have varying impacts on both the seabed and the target and bycatches; especially considering that many designs (all of which are unregulated) can represent more than 20% of the total swept area of some trawl configurations (e.g. for double- or quad-rigs).

Other simple anterior gear modifications might include purpose-built deterrents attached to the anterior sections of trawls (between the otter boards or sleds–to scare fish away), sections of more consistent, appropriate lateral-mesh openings at key strategic locations, and less intrusive ground gears. Applied individually, or in combination, such modifications might reduce bycatches, with many concomitantly lowering drag and therefore improving efficiencies.

It is clear that the utility of anterior gear modifications needs to be assessed and prioritised to provide a coherent basis for future research into improving the economic and environmental sustainability of Australian prawn-trawl fisheries. Such a strategy fits in with previous proven mechanisms for developing modifications to the posterior sections of trawls, and changes to operational and on-board handling designed to mitigate problematic issues (Broadhurst et al., 2006; 2007), and is the approach we followed in this project during more than 22 experiments.

The specific hypotheses tested during each individual experiment are included in the various reports attached here as appendices 3–24. All of this work focused on satisfying the three general objectives listed below.

# Objectives

(1) To identify anterior gear modifications that reduce the bycatch, drag and habitat impacts of prawn trawls, while maintaining target catches and isolate their mechanisms of action.

(2) Using (1) above, provide a framework and direction for the future refinement of Australian prawn trawls.

(3) Investigate the practicality of simple, but appropriate changes identified above under commercial conditions in NSW, and assist local commercial fishers and managers in their implementation, adoption and where appropriate, legislation.

# Methods

## Questions asked (hypotheses tested) about modifications

Each field experiment was designed around specific questions (or, more formally, hypothesis to be tested; see Table 1). While various sub-themes were assessed in each experiment (e.g. concerning factors affecting fish and prawn behaviour), we broadly sought to examine the utility of anterior-trawl modifications that maintained conventional catches of prawns, while either reducing: (1) bycatch (including sizes of the targeted prawns considered too small for sale); (2) habitat impacts (typically with the bottom contact of the otter boards and ground gear as a proxy); or (3) drag/fuel. Further, although reducing drag was not dependant on the other two variables, the converse was required, with any modifications designed to reduce bycatch or habitat impacts also having to demonstrate some potential for concomitantly mitigating drag (and therefore fuel use). The logic behind this approach was that such modifications might be more readily adopted by fishers.

The types of modifications tested varied considerably, but all can be separated by three broad zones of the anterior trawl: (1) spreading mechanisms (including bridles, otter boards, sleds and sweeps); (2) ground gear (or foot rope); and (3) body (wings and belly) (Fig. 1). To further facilitate industry input into the research, virtually all experiments were done using chartered trawlers working in NSW estuaries and offshore. Two ancillary experiments were done using the Australian Maritime College's flume tank. The latter experiments were limited to in-kind project funding, but nevertheless have been included for completeness, and because their results justify subsequent field-based trials.

Depending on the trawling systems and modifications being tested, one of four vessels was used in the field for between 10−20 days during each experiment, with up to eight replicate deployments per day (of between 10−45 min in estuaries and 95−120 min offshore). All trawls used on all vessels had legislated BRDs (e.g. Nordmøre-grids in estuaries and composite square-mesh panels in the ocean). For all vessels and experiments, the general on-board equipment and data collected and their analyses, remained consistent.

## On-board equipment

All chartered vessels had a hydraulic winch located amidships with two independent wire-drums; each fitted with a main wire attached to bridles. The bridles could be passed through blocks either located centrally or on lateral towing arms. Each vessel was equipped with: a fuel monitor (Floscan series); global positioning system (GPS); one or two hull-mounted sum logs (EchoPilot, Bronze Log+); load cells that could be attached to either the bridles (typically in estuaries) or the main wires (in the ocean), and associated data logger (Amalgamated Instrument Company; model nos PA6139 and TP4); and a portable acoustic, trawl-monitoring system (Notus Trawlmaster System; Model no. TM800ET).

The trawl-monitoring system comprised a computer processing unit located in the wheelhouse and an omnidirectional hydrophone; mostly hull-mounted adjacent to the winches, but sometimes deployed over the stern, and two cylindrical transducers and associated slaves (each 330-mm long × 77-mm Ø; 1.1 kg in water). The transducers were encased in mesh bags that could be mounted onto either the trawl wing-ends or otter boards, depending on the experiment.

**Table 1**. Summary of the anterior zone assessed (see Fig. 1 for details), specific questions asked (i.e. proposed hypotheses), treatments tested, fishing location and numbers of days and deployments for each treatment during the various experiments, and the appendix (App.) containing the relevant report. SMO, stretched mesh opening.

| *Anterior zone* | *Were there any differences in the biological and/or engineering performances among…?* | *Treatments* | *Fishing location* | *No. of days/deployments per treatment* | *App.* |
|---|---|---|---|---|---|
| Spreading mechanism | identical trawls spread by a beam or otter boards. | Two 7.26-m trawls (40 mm SMO) were attached to 2.89-m sweeps and either a 107 kg beam-and-sled assembly or a pair of 54-kg (each) cambered otter boards. | Lake Wooloweyah | 9/51 | 3 |
| Spreading mechanism | identical trawls rigged in a (1) dual configuration or a double configuration with bridles that were (2) the same as those used for the dual, or (3) half the length. | Two 7.35-m trawls (42 mm SMO) were attached to 2.89-m sweeps and either two 54-kg otter boards and an 84-kg sled with 36-m bridles in dual rig, or the same otter boards and either 36- or 18-m bridles in double rig. | Clarence River | 10/24, 21 and 23, respectively | 4 |
| Spreading mechanism | single-, double-, triple- and quad-rigged trawls; all with the same cumulative headline length. | The four trawl (42 mm SMO) configurations had cumulative headline and sweep lengths of 14.63 and 9.76 m, with total system weights of 248, 239, 263 and 279 kg, respectively and were optimised for a 10 m (89 Kw) trawler. | Clarence River | 24/36 | 5 |
| Spreading mechanism | different spread ratios (defined as the wing-end spread ÷ headline length) of a generic prawn trawl. | Two 7.35-m trawls (41 mm SMO) were spread using a beam trawl with laterally adjustable sleds, at ratios of 0.5, 0.6, 0.7 and 0.8. | Lake Wooloweyah | 10/30 | 6 |
| Spreading mechanism | identical trawls rigged to otter boards with and without sweeps, and larger, identical trawls rigged to a beam, with and without a 'simple anterior fish excluder' (SAFE). | Otter boards were attached (1) with and (2) without 3.15-m sweep wires to a 7.35-m headline trawl and a beam rigged without sweeps to a larger 9.19-m trawl (to offset a reduction in total contact due to the absence of otter boards) and (3) with and (4) without a SAFE, comprising horizontal wire and plastic streamers across the mouth. | Lake Wooloweyah | 12/36 | 7 |
| Spreading mechanism | the batwing and three conventional otter-board pairs in a double rig. | Batwing (60.7 kg, 1.12 × 1.23 m), flat-rectangular (52.5 kg, 1.39 × 0.61 m), kilfoil (63.0 kg, 1.25 × 0.63 m) and cambered (53.0 kg, 1.08 × 0.73 m) otter board pairs were attached via 2.89-m sweeps to identical 7.35-m trawls. | Clarence River | 3−12/8−24 | 8 |

| | | | | | |
|---|---|---|---|---|---|
| Spreading mechanism | the batwing and two configurations of conventional otter-board pairs in a triple rig. | A pair of batwings (120 kg, 1.40 × 1.30 m) and flat-rectangular (180 kg, 2.00 × 0.84 m) otter boards, with and without a restraining rope designed to regulate angle of attack. were tested with triple-rigged trawls (each 39-m). | Ocean off Yamba | 3/15 | 9 |
| Spreading mechanism | the batwing and flat-rectangular otter boards towed behind a vessel within a system designed to collect disturbed epifauna. | A pair of batwings (60.7 kg, 1.12 × 1.23 m) and flat-rectangular (52.5 kg, 1.39 × 0.61 m) otter boards were affixed in from of a beam and collection trawl (without ground gear) and alternately towed. | Lake Wooloweyah | 6/36 | 10 |
| Spreading mechanism | identical trawls rigged to beam and otter with and without various SAFES. | Three SAFEs, comprising a single wire without, and with small and large plastic panels were tested on paired beam trawls, while one SAFE made from a single wire with a continuous canvas panel was tested on paired otter trawls. | Lake Wooloweyah | 7 and 5/21 and 26 | 11 |
| Ground gear | identical trawls with four different ground gears. | Three ground gears comprised either 6- (4.5 and 3.80 kg in air and water), 8- (8.42 and 6.88 kg) or 10-mm (13.07 and 11.20 kg) stainless-steel linked chain, while the fourth was a novel design termed the 'soft-brush' (15.90 and 6.94 kg) and had a buoyed line with vertically suspended 4-mm link chain (giving 63% less linear bottom contact that the other treatments). | Lake Wooloweyah | 8/24 | 12 |
| Trawl body | trawls with identical frame-line tapers, but different side tapers (long−1N2B vs short−1N5B) and seam numbers (two vs four). | Four 7.35-m trawls (42 mm SMO), with identical frame-line tapers, but either 1N2B or 1N5B side tapers, with two or four seams. | Clarence River | 6/20 | 13 |
| Trawl body | trawls with identical frame-line tapers, but different mesh sizes (32 vs 41 mm) and, within 32-mm mesh, different side tapers (long−1N3B vs short−1N5B) and wing depths (deep vs shallow). | Five 7.35-m trawls; one made from 41 mm SMO (conventional) and the others using 32 mm SMO. Except for mesh sizes, one of the small-mesh trawls was identical to the 41-mm trawl. The four small-meshed trawls had either 1N3B or 1N5B side tapers, with 60 or 97 T wings. Where possible, otter boards were optimised with respect to twine areas. | Lake Wooloweyah and Clarence River | 7/14 and 12/24 | 14 |

| | | | | | |
|---|---|---|---|---|---|
| Trawl body | trawls with identical frame-line tapers, but different mesh sizes (35 and 41 mm) and, within 35-mm mesh different hanging ratios (0.550 and 0.707) and wing mesh orientation (diamond vs square). | Five 7.35-m trawls; one made from 41-mm SMO (conventional) and the others using 35 mm SMO. Within the small-meshed designs, the treatments included (1) increasing the frame-line hanging ratio, and (2) replacing the diamond-orientated wing panel with square-orientated mesh. | Clarence River | 12/24 | 15 |
| Trawl body | trawls with identical frame-line tapers, but different body tapers (1N3B vs 1N5B) fished during the night or day, and for the latter with and without >50% cloud cover. | Two 7.35-m trawls (35-mm SMO), with identical frame-line tapers, but either 1N3B or 1N5B side tapers. The trawls were fished during six days (with varying cloud cover) and four nights on the new moon. | Lake Wooloweyah | 10/44 | 16 |
| Trawl body | triple-rigged Florida flyer, Seibenhauser and 'W' trawls. | Three triple-rig configurations involving (1) three Florida flyer (15.20 m), (2) three Seibenhauser (15.31 m), and (3) two W (18.38 m) and a centre Florida flyer (9.14 m) trawls (all 48 mm SMO). | Ocean off Yamba | 4/18 | 17 |

## Data collected and analyses

In each experiment, various data consistently were collected prior to, during, and at the end of the deployments. Before starting, all treatment trawls, extension sections and codends were measured for replicate mesh sizes to ensure uniformity (where appropriate). Other general data included the location, date, and start time of all trawling days and deployments.

During each deployment, the technical data included the: (1) total fuel (to the nearest 0.1 L) consumed per deployment (period between the trawls on and off the bottom); (2) the total distance trawled (m); (3) tension (kgf) on each of the warps attached to each system (using the load cells); (4) speed (m $s^{-1}$) over the ground (SOG), and (5) through the water (STW); (6) depth fished (m); (7) distance of the system from the vessel (m); and (8) either the wing-end or otter-board spreads (m). Variables 3−8 were simultaneously recorded at ~60-second intervals.

At the end of each deployment, the catches from treatment trawls/configurations were separated into total prawns, bycatch, and in the case of offshore experiments, the 'byproduct' (i.e. non-prawn catches retained for sale) and weighed. Bycatches and byproduct were then separated by species and individually weighed and counted, with subsamples of abundant species measured for total length (TL to the nearest 0.5 cm). Random samples of ~50−200 prawns from the deployment of each treatment were measured (carapace length–CL in mm), weighed and counted. These latter data were used to estimate the total number and mean CL caught from each trawl configuration, during each deployment. Where relevant, the numbers of prawns per 500 g were also quantified.

The hypothesis of no differences in mesh sizes between treatment trawl bodies, extensions and the codends was tested using linear models (LM). Most of the remaining technical and biological data were analysed in linear mixed models (LMM), with some standardised prior to analyses. In many cases, the numbers and weights of total and separated catches were log-transformed (so that effects would act multiplicatively) and analysed as absolute catches per deployment. The raw data were also standardised (mostly to per ha trawled using the swept area between the wing-ends and the distance trawled) and then log-transformed. The remaining biological and technical data (including mean CL and number of Eastern School Prawns per 500 g, drag, wing-end spread, SOG, distance trawled, and fuel used) were analysed in their raw form.

Linear mixed models were fitted to explain variability among key response variables describing the performance of modified configurations (fixed factor) and included various random factors such as 'days' and 'deployments' (and their interaction). In many cases, additional fixed effects/covariates, including SOG, 'flow' (calculated as the speed of the current in the direction of travel and defined as SOG–STW), distance aft of the trawl configuration from the vessel and fishing depth were included in models and assessed for their importance.

All models were fitted using ASReml or the lmer function from the lme4 package of the R statistical language and the significance of trawl configuration determined using either likelihood ratio tests (LRT) or a Wald *F*. Where competing models were assessed, the most parsimonious was chosen based on the lowest value for a penalised log-likelihood in the form of Akaike's Information Criterion. Significant differences detected for the fixed effects of interest were subsequently explored using pairwise comparisons in conjunction with the Benjamini–Hochberg–Yekutieli procedure to control the false discovery rate (FDR; Benjamini and Yekutieli, 2001).

# Results

In total, during 19 field-based experiments, we completed 495 deployments of >30 alternative or new configurations; all of which are summarised in 17 scientific papers, three magazine articles (Table 2 and appendices 3−23) and 16 one-page industry summaries (appendix 24). Two ancillary experiments (and associated scientific papers) were done in the flume tank (Table 3; appendices 19 and 20). In all relevant field-based experiments, the commercial conditions, including catches, were representative of those normally experienced in the fisheries.

For simplicity, the results are summarised according to each of the three anterior zones that were assessed, with efforts (i.e. the number of experiments and/or days and deployments) reflecting the observed utility of a particular zone for addressing the desired outcomes of reducing (1) bycatch, (2) habitat impacts, and (3) drag (Tables 2 and 3). The specific details of each experiment can be found in the stated appendices.

## Spreading mechanisms

In recognition of the importance that the spreading mechanism has with respect to species selectivity (bycatch), bottom contact and drag, 12 of the 19 field and both flume-tank experiments focused on this anterior zone (Table 2, Fig. 5). The key configurations tested included different (1) multiple trawls (i.e. comparisons among single beam trawls and single-, double-, dual-, triple- and quad-rigged otter trawls), (2) spread ratios (SR; defined as the wing-end spread ÷ headline length), (3) bridle lengths within double rig, (4) sweeps within single- and double-rigs, (5) otter boards within single-, double- and triple-rigs, and (6) 'simple anterior fish excluders' (SAFEs) between the otter boards in double-rig and between the otter boards and sleds in triple rig.

The first experiments in the project focused on comparing the relative utility of various existing configurations for affecting the three key response variables, based on the logic that any solutions would be easier to implement (within existing legislation) and understood (by industries). This work showed that substituting single- or double-rigged otter trawls with beams could lower the total system drag by up to 31%, while at the same time reducing the unwanted bycatch of key fish species by up to 79% (as a consequence of the beam visually or physically directing individuals away from the trawl). The inherent spreading mechanism of beam trawls (i.e. two sleds towed parallel) meant that base-plate contact on the seabed was reduced by 85%, for a total system contact reduction of up to 18% (Table 2, Figs 3 and 5).

While less bottom contact might be considered a positive result, we observed that because the otter boards were effective at displacing Eastern School Prawns into the trawls (via their angle of attack, AOA), and their contact represents ~20% of the total system tested (e.g. ground-gear and otter-board linear contact), their removal concomitantly affected catches. Such effects were demonstrated to be partially offset by increasing the size of the beam trawl (by 1.25×), based on the logic that the associated additional ground-gear contact was less intrusive to habitats than otter boards (i.e. a much lower weight). While such a configuration was still not as absolutely effective as the smaller otter trawl in catching Eastern School Prawns, the standardised catches per L of fuel were the same, and with less bycatch (Table 2, Fig. 5).

Within otter-trawl configurations it was clear that while relative system efficiencies reflected a complex array of interacting factors, environmental performance improved with an increasing number of trawls in the system and/or fewer otter boards. Of all the configurations tested (Fig. 2), the single rig had the least fishing capacity due to having the lowest SR, but the greatest drag (and therefore required the most fuel; Table 2). Further, the single rig caught significantly more fish (e.g. Yellowfin Bream) than any of the multi-net rigs (Table 2).

**Table 2.** Details of the anterior zone (see Fig. 1 for details) and specific treatments tested, and their relative (compared to conventional configurations) effects on catches, bottom contact and drag (as a proxy for fuel usage). App, appendix containing the relevant report. [D]double- or [T]triple-rig used in testing, *significant difference ($p < 0.05$), SMO, stretched mesh opening.

| *Anterior zone* | *Treatments tested* | *Catches* | *Bottom contact* | *Drag* | *App.* |
|---|---|---|---|---|---|
| Spreading mechanism | Beam vs otter trawl[D] | Beam trawl caught 33 and 79% fewer* Eastern School Prawns and Southern Herring per ha than the otter trawl. | Beam trawl had 18% less total bottom contact. | Beam had 10% less* drag. | 3 |
| Spreading mechanism | Dual- vs double-rig (with long and short bridles)[D] | Dual rig caught 35 and 61% fewer* Eastern School Prawns and mulloway per ha than double rig. Bridle length affected SR, but not catches. | Dual rig had 19−26% less total bottom contact than double rig. | Dual rig had 24% less* drag | 4 |
| Spreading mechanism | Single- vs double- vs triple- vs quad-rigged trawls[D,T] | Compared to all other configurations, single rig caught the most* Yellowfin Bream per ha trawled. There were no differences in Eastern School Prawn catches per ha trawled among configurations. | Triple- and single-rigs had 2−16% less total bottom contact than quad- and double-rigs. | Triple- and quad-rigs had incrementally less* drag than single- and double-rigs (by up to ~11 and 4%). | 5 |
| Spreading mechanism | Spread ratios (SR) of 0.5 vs 0.6 vs 0.7 vs 0.8[D] | Incrementally fewer* Eastern School Prawns were retained (by up to 51%) per ha with increasing SR, while the three highest SRs caught fewer fish* (by up to 30%) per ha than the 0.5 SR. | Increasing SR increased bottom contact by the stated proportions. | Increasing SR incrementally increased* drag by up to 16%. | 6 |
| Spreading mechanism | Otter trawls with and without sweeps vs beam trawls (1.25 × larger) with and without a ‘simple anterior fish excluder’ (SAFE)[D] | While the otter trawl with sweeps caught more* Eastern School Prawns, removing sweeps, using a beam or adding a SAFE reduced* the bycatch of Southern Herring by up to 48%. | Total system contacts among treatments were similar, but the beam trawls had 85% less base-plate contact. | Both beam trawls had up to 31% less* drag than the otter trawls. | 7 |
| Spreading mechanism | Batwing vs flat-rectangular vs kilfoil vs cambered otter boards[D] | Trawls spread by the cambered otter boards retained up to 13% more* Eastern School Prawns per ha than the other treatments, but otter boards had no effects on fish catches. | Compared to the four other designs, the batwing had 86% less bottom contact. | Compared to the four other designs, the batwing had 18% less* drag. | 8 |

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|---|---|---|---|---|---|
| Spreading mechanism | Batwing vs flat-rectangular otter boards with and without a restraining wire (SAFE)[D] | Otter boards had no effect on Eastern King Prawn catches per ha trawled, but the restrained trawls caught up to 19% less* bycatch than those spread conventionally, or by the batwings. | Compared to the conventional otter boards the batwing and restrained configuration had 88 and 40% less bottom contact. | Compared to the other configurations, the batwing had 5% less drag*, but some of this was explained by a confounding effect of different SRs. | 9 |
| Spreading mechanism | Batwing vs flat-rectangular otter boards (habitat impacts)[D] | Compared to a conventional flat-rectangular otter board, the batwing displaced fewer* Eastern School Prawns and Bridle Gobies (by 78 and 25%). | Compared to a conventional flat-rectangular otter board, the batwing displaced 89% fewer* shells and damaged proportionally* less. | Not assessed. | 10 |
| Spreading mechanism | Beam and otter trawls with and without various SAFEs[D] | All SAFES maintained target catches of Eastern School Prawns (per ha), but reduced* total bycatch by up to 51% and Tailor, Sea Mullet and Southern Herring by up to 58%. | No effects. | No effects. | 11 |
| Ground gear | Soft-brush vs 6-mm, vs 8-mm, vs 10-mm chain ground gears[D] | Ground gear had no effect on catches of Eastern School Prawns, but 45% fewer* Forktail Catfish were caught by trawls with the 6-mm chain than the 10-mm or soft brush. | The soft brush had 63% less linear bottom contact than the conventional ground gears. | Ground gears accounted for between 15 and 22% of the total tested system drag, and their modification in conventional systems could reduce drag by ~5%. | 12 |
| Trawl body | 1N2B two-seam vs 1N2B four-seam vs 1N5B two-seam vs 1N5B four-seam[D] | Catches of Southern Herring were 66% lower* in the 1N5B trawls, but owing to too large a mesh size (42 mm SMO), catches of Eastern School Prawns were also reduced* (by 50%). | No effects. | Compared to the longer 1N3B trawls, the shorter 1N5B designs reduced* drag by 4.3%. | 13 |
| Trawl body | Small-meshed (32 mm SMO) 1N3B deep wing vs 1N3B shallow wing vs 1N5B deep wing vs 1N5B shallow wing vs a conventional 41-mm trawl[D] | Side taper and wing depth had interactive* and varied effects on catches, but compared to the conventional 41-mm trawl, the 1N5B shallow-wing design (least twine area) reduced* fish bycatch by 57% with no effects on Eastern School Prawns. | No effects. | There were incremental drag reductions* of up to 18% associated with reducing twine area via either shorter bodies or shallower wings. | 14 |
| Trawl body | Tightly-hung frame line with diamond- or square-mesh wings vs | Compared to the conventional 41-mm trawl, the shorter smaller-meshed trawls caught fewer fish, | No effects. | Compared to the conventional trawl, all four shorter small-meshed | 15 |

| | | | | | |
|---|---|---|---|---|---|
| | loosely-hung frame line with diamond- or square-mesh wings vs a conventional 41-mm trawl[D] | while the trawls with the square-mesh wings reduced* the catches of undersize Eastern School Prawns by 54−72%. | | designs reduced* drag by 9−12%. | |
| Trawl body | 1N3B vs 1N5B trawls (35 mm SMO) during variable ambient light[D] | Compared to a long (1N3B) trawl, a short (1N5B) trawl consistently caught fewer* undersize Eastern School Prawns, but only reduced* catches of Southern Herring (by up to 40%) when there was sufficient ambient light. | No effects. | Not assessed. | 16 |
| Trawl body | Florida flyer vs Seibenhauser vs 'W' trawls[T] | The Florida flyer retained the most* standardised catches of Eastern King Prawns and bycatch, followed by the Seibehauser and W-trawl configurations. | No effects. | Compared to the conventional triple rigs, the W-trawl configuration required* less fuel per hectare (by up to~4%). | 17 |

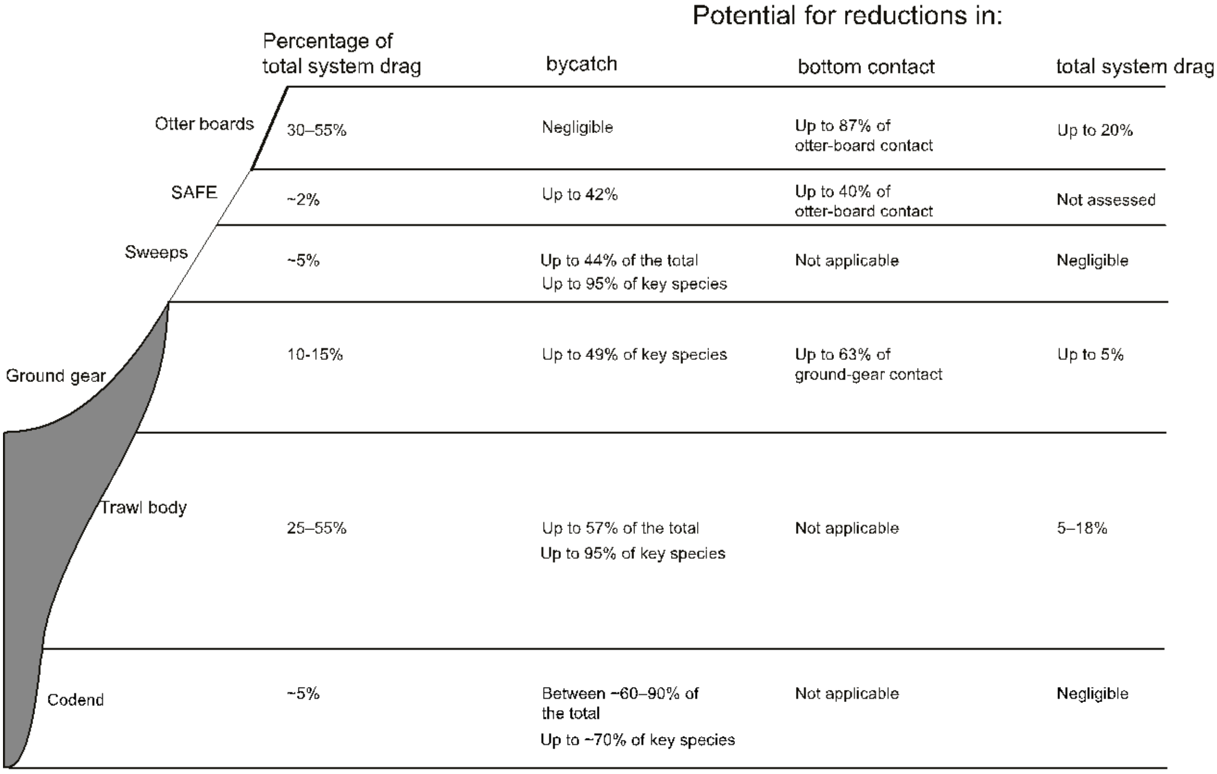


**Figure 5.** Schematic representation of the key anterior trawl components, their contributions towards total system drag and the potential for reductions in bycatch, bottom contact and drag through individual modifications. Codend data (from previous literature) are included for comparative purposes.

Compared to single rig, double rig had an improved SR and less drag (Table 2). Although not tested concurrently with all systems, dual rig offered more drag benefits that double rig and also caught significantly fewer small (<9.5 cm TL) Mulloway (by 61%). But, the effects of removing two otter boards manifested as some reduction in Eastern School Prawn catches (although this was offset by 24% lower drag; Table 2). Of all the tested systems, triple- and quad-rigs achieved the greatest SRs and at lower drags (by up to 11%) than single- and double-rigs. Triple rig had the additional advantage of reducing total bottom contact (i.e. via two fewer otter boards), although based on our experiments with dual rig, quad rig might be expected to catch relatively fewer individuals of some species. This assumption requires testing as part of future research.

Irrespective of the spreading mechanism, the engineering and catch implications of regulating the SR were highlighted as being very important. For example, incrementally increasing SR from a baseline of 0.5 to 0.6, 0.7 and then 0.8 using a purpose-built beam trawl significantly increased drag (by up to 16%) without affecting absolute catches. But when catches were standardised to per ha trawled, significantly fewer Eastern School Prawns and total bycatch were retained in the wider-spread trawls; potentially because the steeper wing angles increased the probability of mesh encounters for Eastern School Prawns and were less efficient at herding fish (Table 2).

One spreading mechanism variable shown to affect SR within systems was the bridle length, although the magnitude of differences precluded concomitant effects on engineering and catching performances. Specifically, at a constant speed (~1.31 m $s^{-1}$), halving the bridle length in double rig (from 36 to 18 m), significantly reduced the SR from 0.61 to 0.58, but without affecting drag or the catches of Eastern School Prawns or bycatch (Table 2).

Conversely, eliminating sweeps (2.89 m) in double rig had a similar magnitude of effects on SR (albeit in the opposite direction with an increase from 0.67 to 0.71) without affecting drag, but strongly affected catches (Table 2). The latter manifested as fewer Eastern School Prawns and unwanted fish (mostly Southern Herring) per ha of up to 29 and 50% in the absence of sweeps. The lower Eastern School Prawns catches were attributed to the proximity of the otter boards to the trawl (and some individuals flicking over the headline), while removing sweeps was thought to reduce the herding of fish into the trawl (Table 2).

Owing to the identified importance of SR, wherever possible, we attempted to maintain comparable values among treatments in all experiments, and especially with respect to testing otter boards (mostly done within double rig). This outcome was considered essential to fully identify the potential (or otherwise) of different designs of otter boards for mitigating drag, while maintaining catches.

The latter work involved two flume-tank and three field experiments. The flume-tank work was done to identify appropriate rigging arrangements of simple sails used on the batwing as a precursor to field trials (Table 3, Fig. 3). These experiments identified a functional AOA of 20$^{o}$ and optimal sail shape with appropriate twist and camber (Table 3).

**Table 3.** Two flume-tank experiments to evaluate sail hydrodynamics of the batwing otter board. App. Appendix containing the relevant report.

| *Treatments tested* | *Key results* | *App.* |
|---|---|---|
| One battened sail under various angles of attack (AOA) and with five combinations of twist and camber. | A 20$^{o}$ AOA and with medium twist and camber provided a lift-to-drag ratio >3, which is three× more than that of contemporary otter boards and should provide up to 20% drag savings. | 19 |
| Battened vs high-rake sails under various AOA and with five combinations of twist and camber. | A 20$^{o}$ AOA was ideal for all combinations, within which optimal performance and stability were achieved with high twist and low camber for the high-rake sail and medium twist and camber for the battened sail. | 20 |

In the first series of otter-board field experiments, we showed that compared to three conventional designs (flat-rectangular, cambered and kilfoil), an appropriate-sized batwing had up to 18 and 86% less drag and bottom contact respectively, without significantly affecting catches of Eastern School Prawns nor bycatch. Among the conventional otter boards, the cambered design caught more Eastern School Prawns per ha (up to 13%), attributed to its greater solid profile—reiterating the importance of otter boards in affecting catches of this species.

Subsequent work to assess relative habitat disturbances between the batwing and the flat-rectangular revealed that the former displaced significantly fewer empty shells at a rate closely correlated to the reduction in base-plate contact (by 87%; Table 2). Further, the batwing damaged proportionally fewer shells, attributed to their displacement away from the otter board's surface area (instead of rolling along the angled base plate). Other debris (lighter pieces of wood) were not as greatly mobilised; possibly owing to their position slightly off the bottom, and a more common influence of hydrodynamic displacement by otter-board surface areas (rather than the base plate on the substratum).

In another preliminary experiment, we attempted to replicate some of the characteristics of the batwing (i.e. its low AOA) by retrospectively adjusting the configuration of a conventional flat-rectangular otter board with a restraining line at the anterior edge to regulate the AOA to < 30$^{o}$ (Table 2). This work was done using a triple rig and also involved assessing the batwing. Neither the restrained flat-rectangular nor batwing significantly reduced drag (attributed to a low contribution of otter boards to the total drag of triple rig), but both considerably reduced otter-board contact on the sea bed, without affecting catches of Eastern King Prawns per ha trawled. More specifically, the restrained flat-rectangular and batwings had 40 and 88% less lateral bottom contact, which manifested as ~4 and 8 ha less bottom contact by the heavy otter boards during one night's fishing by the trawler.

The latter results have encouraging implications for minimising habitat disturbance. Specifically, if a typical Australian prawn trawler towing two trawls had its four conventional otter boards (i.e. each with a length of 2.13 m at 35° AOA) replaced with batwings, then the bottom contact of heavy steel (>250 kg being dragged obliquely) would be reduced by ~0.19 $km^2$ (>10 times the ANZ Stadium oval) over one fishing night (8-hours trawling). If only 110 vessels (~10% of the national prawn trawling fleet) used the batwings for 120 nights, the total reduction in bottom contact would amount to an area greater than the Australian Capital Territory (2,358 $km^2$).

The trawls spread by the restrained flat-rectangular otter boards also caught significantly less bycatch (by up to 37%); a result attributed to the line providing a visual or tactile stimulus that herded some individuals away from the path of the trawl. We labelled this configuration the SAFE, and initially demonstrated its performance during two experiments on double-rigged trawlers towing beam- and otter-trawls (Table 3, Fig. 6).

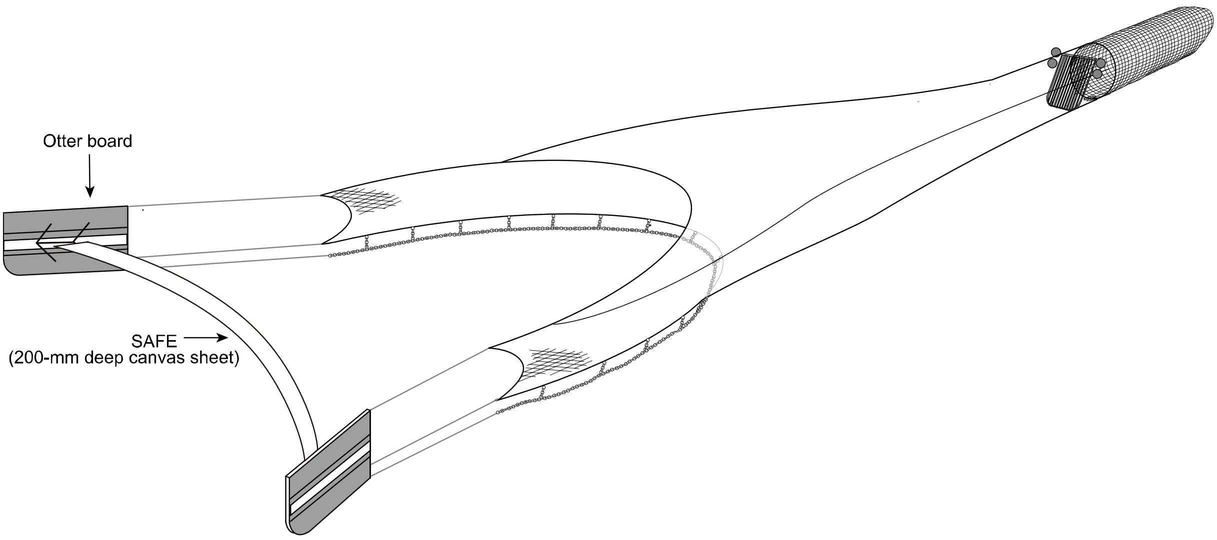


**Figure 6.** A simple anterior fish excluder (SAFE) tested as part of the experiment described in Appendix 11.

Compared to controls, the SAFE prototypes tested on double rig maintained the catches of Eastern School Prawns per ha trawled, but significantly reduced total bycatch by up to 51% and the numbers of individual species, including Tailor, Sea Mullet and Southern Herring by up to 43, 58 and 49%, respectively (Table 2, Figs 5 and 6). The SAFEs were by far the most effective on beam trawls, but still significantly reduced the catches of key fish among otter trawls. The SAFE concept warrants substantial future testing (see Discussion).

## Ground gear

Within conventional otter trawls, the ground gear was identified to contribute towards <15% of the overall system drag (Table 2, Fig. 5). Therefore, within the scope of the project we considered this area to have less overall impact than the other two anterior zones in terms of mitigating drag. Nevertheless we demonstrated the potential for improvements to design, without negatively affecting trawl performance for the targeted species.

The relevant study involved testing four ground gears; three of which comprised either 6- (4.5 and 3.80 kg in air and water), 8- (8.42 and 6.88 kg) or 10-mm (13.07 and 11.20 kg) stainless-steel linked chain. The fourth was termed the 'soft-brush' (15.90 and 6.94 kg) and had a buoyed line with vertically suspended 4-mm link chain, which compared to all other designs reduced bottom contact by

63%. The three chain and soft-brush ground gears were used during 24 deployments, producing predicted mean drags (±SE) of 25.49 (1.50), 31.28 (1.50), 39.32 (1.50) and 31.93 (1.50) kgf respectively, or 15, 18, 22 and 18% of the tested beam trawl. In terms of an otter trawl, such figures would translate to a ~5% reduction in drag if the 6-mm chain was used instead of the 10-mm (Table 2, Fig. 5).

There were no significant differences in numbers or weights of the targeted Eastern School Prawns, although the predicted means were up to 16% lower in the trawls with the 6-mm ground gear. The only species significantly affected by ground gear was small (5.0−8.5 cm TL) Forktail Catfish with the 6-mm catching up to 45% fewer than the 10-mm and soft-brush ground gears; a result attributed to the latter ground gears having greater surface areas (and therefore providing more visual and/or tactile stimuli). While the drag benefits were minimal, more work needs to be done to determine the extent to which the bycatch of benthic organisms can be reduced by modifying ground gears.

## Trawl body

Six of the 19 field experiments were devoted to testing hypotheses concerning the utility of modifications to the trawl body to address the key response variables; which, because the trawl body does not impact on the seabed, were restricted to reducing bycatch and drag. At the broadest level, all trawl-body modifications involved the underlying concepts of (1) minimising twine area, while (2) maintaining appropriate lateral mesh openings for the targeted prawns.

The first experiment investigated the utility of reducing twine area by steepening the side taper of existing conventional two- and four-seam Clarence River trawls (42 mm SMO) from 1N2B (or 25$^o$) to 1N5B (35$^o$), which effectively shortened the bodies by 3.6 m (or 35%). The consequences of this simple change were profound and consistent within seam number (two vs four), manifesting as significant reductions in drag (by 4.3%) and standardised (per ha) catches of Southern Herring (by 66%) among the shorter trawls (Table 2). However, the short trawls also retained significantly fewer (by 50%) Eastern School Prawns (biased towards smaller individuals). These catch reductions were attributed to the shorter 1N5B bodies increasing the probabilities of mesh encounters (both species) and allowing Southern Herring to swim forward and escape, while Eastern School Prawns passed through.

The first trawl-body experiment (above) provided the evidence required to demonstrate that the legislated minimum mesh size of 40 mm SMO used in Clarence River trawls is too large. Consequently, we reduced the mesh size to 32 mm and tested the same hypothesis above concerning side taper (but 1N3B−28$^o$ vs 1N5B), and also another modification for reducing twine area: lowering the wing height (i.e. we tested ‘deep’−97 T vs ‘shallow’−60 T). As part of this work, we also reduced otter-board surface areas to more closely match the lower twine areas of the relevant trawls.

During two experiments, we observed incremental drag reductions (by up to 18%) associated with reducing twine area via either modification (and subsequently minimising otter-board area) (Table 2). Side taper and wing depth had interactive and varied effects on bycatch reduction, but compared to a conventional 41-mm trawl, a 32-mm short shallow-wing trawl (i.e. with the least twine area and 20% smaller mesh size) reduced the total bycatch by 57% (attributed to more fish swimming forward and escaping). This is an important result that clearly demonstrated mesh size in the trawl body is not the most important variable affecting selectivity. All small-meshed trawls also caught more smaller Eastern School Prawns than the conventional trawl, but we proposed that it should be possible to increase mesh size slightly, while still maintaining the above engineering benefits and species selectivity (Table 2).

The latter hypothesis was subsequently tested as part of a fourth experiment with mesh size and side taper. Specifically, we fished the same conventional 41-mm trawl as above (i.e. with a 1N3B side taper) against four trawls; all made from 35-mm mesh and with 1N5B side tapers. Within the smaller-meshed trawls we assessed the independent and combined utility of (1) increasing the frame-line hanging ratio (E; defined as the stretched length of a hanging line or operating opening of a mesh panel divided by the stretched length of the mesh panel) from a conventional 0.550 to 0.707, and (2) replacing the diamond-orientated wing panel (20 T) with square-orientated mesh (i.e. 20 B; Table 2).

Compared to the conventional 41-mm trawl, all four smaller-meshed designs (comprising either loose or tight hanging ratios, and with diamond- or square-mesh wings) had lower drags (9−12%; Table 2). Like the earlier two experiments described above, some of the shorter, small-meshed trawls also caught fewer unwanted fish (by up to 38%). Further, there were incremental improvements in size selectivity for Eastern School Prawns associated with both changing hanging ratio and wing-mesh orientation. But the square-mesh wing panels were by far the most effective, reducing the catches of sub-commercial Eastern School Prawns by up to 72%, without reducing catches of the targeted sizes (Table 2).

The observed variability in the extent of bycatch reduction (i.e. between 38 and 51%) by the short (1N5B) trawls described above precipitated a fourth experiment to more closely investigate causal effects and more specifically, the importance of available ambient light (on fish and Eastern School Prawn behaviour). During this experiment we compared two identical trawls (both made from 35 mm SMO) that differed only in their side tapers (1N3B vs 1N5B). The trawls were fished during the night and in the day with variable cloud cover (categorised as <50 and >50%). Catches were dominated by Eastern School Prawns and seven species of fish. Only two fish species (Southern Herring and Australian Anchovy) along with the Eastern School Prawns were significantly affected by side taper, with all retained in lower numbers by the shorter (1N5B) trawl. For Eastern School Prawns and Australian Anchovy, their catch reductions mostly remained consistent irrespective of diel phase and diurnal cloud cover, but Southern Herring (mostly smaller individuals) only escaped from the short trawl during diurnal deployments and with <50% cloud cover; possibly through anterior meshes in response to more available ambient light.

While it was clear that available light was important for Southern Herring in escaping from trawls, our last experiment with trawl bodies demonstrated that that other species behave differently and can still respond to trawls at low light levels. Specifically, compared to conventional, triple-rigged Florida flyer trawls (body taper of 1N4B) we observed a significant reduction in the standardised catches of Red Mullet and Longspine Flathead from triple-rigged Seibehauser and so-called ‘W’ trawls. Both had considerably steeper side tapers. However, at least some of these fish were small enough to escape through the meshes; an effect that also contributed towards a reduction in caches of Eastern King Prawns. The W-trawl configuration also required less fuel per hectare (up to 4%), although additional refinements are required to maximise performance.

# Discussion

The results of this project clearly demonstrate that the three environmental concerns of excessive bycatch and drag and perceived habitat impacts associated with prawn trawling can be dramatically mitigated by employing one or more of three groups of modifications to the anterior trawl: (1) selecting an appropriate multi-trawl configuration, (2) reducing otter-board AOA to ~20$^{o}$, and/or (3) minimising the twine area. Irrespective of these modifications, a fourth all-encompassing operational variable is maintaining an appropriate SR. The relative utility of these strategies can be discussed according to the underlying biological and engineering consequences. Ultimately, this information can be used to identify practical solutions within a framework for the future refinement of anterior gear modifications to improve the profitability and environmental performance of Australian prawn trawling.

## Select the most appropriate multi-trawl configuration

The first step in the framework is to select the most appropriate conventional configuration; a decision that will largely depend on fishery-specific operational characteristics and existing legislation. It is clear that where a single trawl is desired, then beams and possibly their derivatives (e.g. winged trawls, like the 'sumwing'; http://www.sumwing.nl/SumWing_EN.pdf) could be a good option. We clearly showed that beam trawls inherently are easy to tow, and have good species selectivity owing to the solid structure scaring fish away from the front of the trawl (via either visual or tactile stimuli). If necessary, the size of the beam trawl might be increased slightly to compensate for any loss of target catches due to the loss of bottom contact by otter boards. Beams might also be used in higher order multi-trawl configurations, but better methods of storing and deploying the gear (e.g. perhaps some sort of joint in the middle of the beam to facilitate handling on board) are required (Gillett, 2008).

Within prawn otter-trawl systems, there seems minimal utility in promoting single gear, unless fish are a desired by-product. Perhaps a more suitable strategy is to use quad rig for shallow water (instead of double rig), and triple- or penta-rigs for deep water (if a single/double beams is not an option). By definition, increasing the number of nets reduces twine area. Also, because sleds are used in quad- and triple-rigs, they require smaller otter boards; which means less total system contact (and presumably habitat-impact reductions). As one example, we showed that for the same vessel (10 m and 89 kw), triple- and quad-rigs had up to 55% less base-plate linear contact than double- and single-rigs. Even with their greater SRs, triple- and quad- rigs still have less overall bottom contact (by up to 9% over double rig).

Although we only did one experiment with ground gear, irrespective of the spreading mechanism or trawl configuration, further reductions in bottom contact could be realised by using alternate systems like the soft brush. Compare to conventional, chain ground gears, the soft brush reduced the bottom contact by 63%, with no effect on target catches. Other ground gears warrant assessment, and possibly those including angled cups to displace water downwards to stimulate prawns via hydrodynamic pressure instead of physical contact. Such configurations have been proposed for use with scallop dredges (Shepard et al., 2009) and would greatly minimise the bottom contact of benthic otter trawls.

Any reduction in otter-board height associated with more trawls within a system (especially for quad rig) would concomitantly reduce headline height (e.g. by >16% of a double rig); a modification which although not directly studied here, has been demonstrated to reduce fish catches in other trawls (e.g. Rose and Nunnallee, 1989). Further, reducing the number of otter boards may translate to fewer fish being herded into the trawl—considering we showed that compared to single rig, triple rig caught 44% fewer fish, while identical trawls towed in a dual rig caught up to 60% fewer Mulloway than those in a double rig.

Quad rig encompasses the same three-wire bridle configuration as dual rig, and might return similar benefits in terms of bycatch reduction. These configurations (and others with sleds) warrant further testing during periods of high fish abundances (e.g. Mulloway in the Clarence River).

**Framework**

1). Select the most appropriate multi-trawl configuration

- Choose a conventional configuration with a bias towards sleds, including: a single beam, or triple- or quad-rigged otter trawls.
- Explore the potential for installing SAFEs between spreading mechanisms.

2). Reduce otter-board AOA to ~20º

- Choose conventional configurations with the lowest stable operating AOA.
- Explore the potential of retrofitted modifications to existing designs for reducing AOA.
- Explore the potential of novel designs like the batwing.

3). Minimise twine area

- Optimise mesh size and twine diameter for the targted organisms and then reduce trawl body to the shortest practical length by maximising side taper and minimising wing height.
- Explore the potentail for increasing lateral mesh openings at strategic positions, via square-mesh panels or T90, as a means for reducing unwanted catches.
- Explore the potentail for minimising twine area via alternative trawl designs like the W-trawl.

4). Optimise spread ratio

- Optimise the spread ratio within a defined range for the desired trawl system.

**Figure 7.** A framework of anterior gear modifications for reducing the environmental impacts and improving the profitability of prawn trawling, with the need for future work encapsulated by the sub-themes preceded by ‘Explore’.

One limitation of quad rig is the need for four codends, which can increase on-board handling and BRD maintenance. A possible solution to this issue while maintaining the three-wire bridle-configuration benefits is to use tongue trawls like the W trawl tested here (see also Watson et al., 1994). Although clearly, such designs need to maintain target catches at the existing levels of conventional rigs, while significantly reducing drag (Table 2).

Irrespective of the configuration, it is also clear that additional stimulus in front of the spreading mechanism can promote fish avoidance. We assessed a SAFE between the otter boards, but similar configurations could be rigged further forward of the trawl, including via the three-wire bridle in quad rig or a W trawl, or some similar arrangement with triple- or double-rigs (Fig. 8). Ideally, to prevent fish entering the trawls, such SAFEs would have convex, rather than concave shapes. These types of designs have been theorised (e.g. Ryer, 2008) and definitely warrant extensive ongoing assessment, which might be expanded to include the utility of other stimuli, including light. Any such SAFEs would need to be designed so that they can pass through the blocks (and possibly the winch) on the vessel.

Based on our diel experiment with a short body, the SAFEs probably mostly operate via visual stimulus; but nocturnal use in clear water may not preclude their effectiveness. In particular, we observed a significant reduction in bycatch by the SAFE rigged to the outside trawls of a nocturnally fished triple rig, and so presumably under the right conditions at least some fish can still see the device at night. Similar visual responses have been hypothesised to account for the escape of fish through behavioural-type BRDs in nocturnally deployed trawls (Broadhurst et al., 1996).

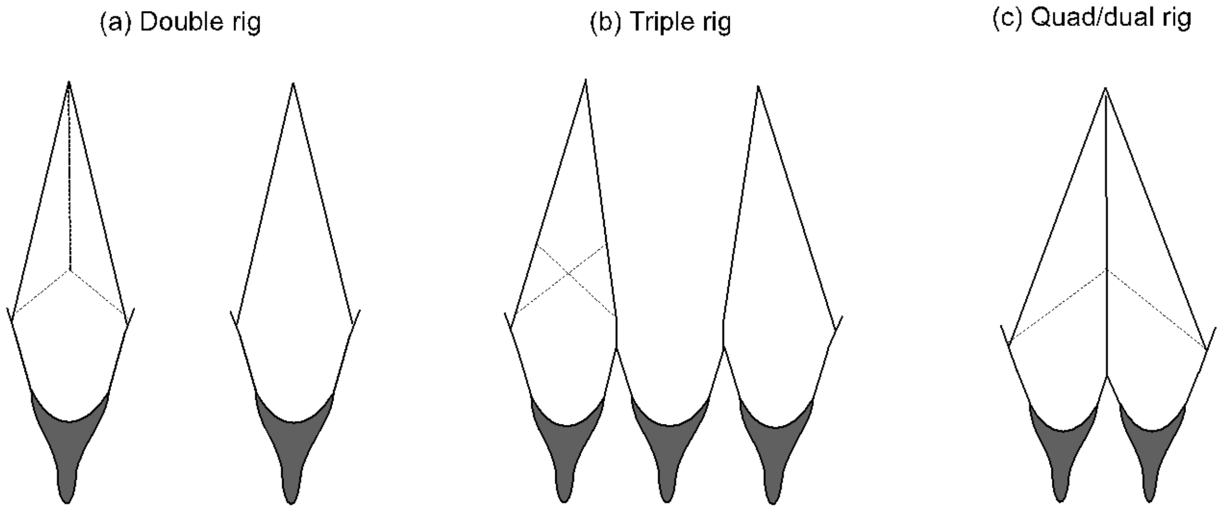


**Figure 8.** Potential orientations of simple anterior fish excluders (SAFE− dotted lines) in (a) double-, (b) triple-, and (c) quad- or dual-rigs.

## Reduce otter-board AOA to ~20$^o$

The second framework step is to strike a balance between the maximum effectiveness and efficiencies of otter boards, which can be approached when the AOA is ~20$^o$ (an outcome that also reduces bottom contact). For conventional designs, one option for optimising AOA might be to locate a SAFE between the leading edges. We were able to functionally reduce the otter-board AOA in triple rig using a SAFE (between the otter board and sled), although the greatest benefits should be between two otter boards in double- or quad-rigs. Restraining otter-board pairs to ~20$^o$ AOA should have significant benefits for the drag of these systems and warrants further testing. One additional advantage of a SAFE in small-scale fisheries, might be as a precursor to foul-ups on debris (e.g. in rivers/estuaries), whereby the SAFE would contact the obstruction first and collapse the otter boards—potentially preventing the netting from being ensnared and damaged.

Other simple, retroactively fitted options still need to be explored to reduce conventional otter-board AOA during fishing, but in the interim the batwing concept offers a real solution for not only minimising drag (by up to ~20%), but also bottom contact. The design has a comparable cost to conventional otter boards, and is a viable option in those fisheries where there are concerns over habitat impacts. For example, a batwing or similar sled-type spreading mechanism (e.g. beam) can reduce the heaviest contact of a prawn-trawl system by nearly 90%. In terms of a practical example, if a NSW oceanic triple-rigged trawler was to use the batwing otter boards, they would effectively reduce the bottom contact of heavy steel being dragged obliquely by ~8 ha over one night of fishing (8-hours trawling). Multiply this estimate by 100 trawlers fishing 150 nights a year (e.g. an entire fleet) along the NSW coast, and the area saved from such contact would be 120 000 ha (1200 km$^2$).

While there are no data on the consequences of such a massive reduction in otter-board contact, intuitively the benefits might include at least some reduction in collateral mortalities of prawns and sedentary organisms. In any case, we showed that the batwing otter boards didn’t negatively affect the target catches. Rather, based on our data, the batwings actually increased the catches of some by-product species in triple-rigged trawls.

Other, novel otter boards warrant testing, including modifications to conventional designs to minimise their bottom contact. Kennelly and Broadhurst (2002) suggested placing angled sleds or rollers on otter boards as mechanisms for reducing footprint. Further work is required to more closely assess the habitat benefits of any such modifications.

## Minimise twine area

Once the correct trawl configuration and otter boards have been selected, the third step in the framework is to minimise twine area. Within this theme, an ancillary outcome of our work was reiteration that first and foremost, the most important preliminary criterion is to optimise mesh size for the targeted species. It was clear from the outset that the legislated minimum 40 mm SMO used in Clarence River trawls is too large for the targeted Eastern School Prawns (<~25 mm CL). Once a more appropriate mesh size was used (e.g. ~35 mm SMO), we showed that within a conventional trawl design, shortening the body (up to 35%) by steepening the side taper and/or reducing wing height was the simplest mechanism for reducing the twine area and therefore drag (by up to 18%).

Equally importantly, shortening the trawl body allowed some fish to avoid capture. The reduction in fish catch can be explained by individuals visually detecting the steeper netting panels and swimming forwards and escaping (especially during haul-back; Broadhurst et al., 1996); either from the mouth of the trawl, or through the opening of the BRD (a Nordmøre-grid). This hypothesis is supported by our study of diel effects on short trawl bodies. We showed that more Southern Herring escaped from shorter trawls during periods of brighter light, when presumably they could more easily see the steeper netting panels (Kim and Wardle, 2003).

Owing to their limited behavioural responses to trawls, Eastern School Prawns were not as greatly affected by shorter nets. After entering the net (presumably in response to tactile stimuli from the ground chain), prawns would have fairly quickly tumbled down the netting panels and towards the bag (Watson, 1989). Some smaller individuals were then selected through the meshes, but if an appropriate mesh size is used (e.g. ≥35- vs 40-mm SMO for the Clarence River fishery) there should be no loss of commercial-sized individuals.

In addition to reducing the wing height to concomitantly reduce trawl body length, altering the mesh orientation down the sides of the trawl provided clear benefits in terms of size selectivity. Clearly, large quantities of Eastern School Prawns contact this area of trawls, with only a small 20-bar (e.g. ~360-mm high) square-mesh side panel reducing >70% of sub-commercial (<15 mm CL) individuals. Increasing the frame-line hanging ratios to improve lateral mesh openings (immediately posterior) did not have the same level of effect, but the utility of larger panels of square- or T90 meshes in the sides and/or the top belly of the trawl warrant investigation for their utility in further improving selectivity.

## Optimise spread ratio

Irrespective of the anterior configuration, it is imperative to achieve optimal SR; making this an important last step in the framework. It is well established that the SR in benthic fish trawls can vary according to a plethora of technical and environmental factors including the towing speed, current, sea conditions, bottom type, warp length and fishing depth (e.g. Engås and Godø, 1989; Fujimori et al., 2005; Weinberg and Kotwicki 2008). Even subtle variations in the SR of fish trawls can change the geometry (including headline height) sufficiently enough to ultimately affect catches (e.g. Rose and Nunnallee, 1998; Weinberg and Kotwicki, 2008) and drag (Sala et al., 2008).

We observed that the above impacts extend to prawn trawls, with an increasing SR positively associated with drag (increasing by up to 16% from an SR of 0.5 to 0.8) and, when catches were standardised to per ha trawled, a clear negative relationship with catch efficiency for Eastern School Prawns, and a comparable trend for the weight of bycatch.

We mostly attributed these results to the similar effects of shorter trawl bodies, with more Eastern School Prawns escaping from the wider-spread trawls owing to their steeper netting panels and some fish more easily detecting the trawls and not entering. Unlike shortening the trawl body which reduces twine area, steeper netting in an over-spread trawl simply increases resistance and therefore drag.

Beyond the importance of optimising SR to maximise the engineering and environmental performance of particular prawn-trawling configuration are the implications for fishery-independent trawl surveys, which typically assume minimal variation in SR. But it is clear that unless SR is regulated, there could be confounding effects on indices of relative abundance. One way to simply regulate SR in survey trawls would be to locate a restraining line between the otter boards or across the bridle, or to use beam trawls.

Finally, SR needs to be considered in any fishery where headline length is used as a tool to manage effort. Even slight variations (e.g. from 0.5 to 0.6) ultimately affect the swept area. For example, a 10-m trawl with an SR of 0.5 sweeps 5 m, while the exact same trawl at 0.8 SR covers 8 m. Clearer understanding of the key factors affecting the engineering and catching performances of prawn trawls will facilitate coherent fisheries management.

# Conclusions

Prawn-trawl fisheries face serious sustainability issues that encompass both energy usage and ecosystem impacts. This project sought to provide clear direction for ongoing strategic fishing-gear research involving modifications to holistically address these broad concerns.

The first project aim was to identify/isolate physical modifications to the anterior trawl that provide a range of positive inputs towards holistically minimising impacts, and clearly this has been satisfied. Unlike BRD research in the past, which resulted in few perceived short-term benefits to industry, the energy savings associated with key anterior modifications should help encourage their adoption. Ultimately, the potential for reductions in unaccounted fishing mortality (which rival those observed for BRDs) should enormously improve the sustainability of prawn trawling.

The key categories of modifications detailed in this project encompass spreading mechanisms, ground gear, and the trawl body; with various individual and cumulative benefits. Potentially, combinations of appropriate modifications (e.g. batwing otter boards, short trawls and soft-brush ground gear) could reduce drag (and therefore fuel) by up to ~30%, total and key species bycatches by up to ~55 and 95% respectively, and total system bottom contact by >70%; all without significantly impacting on target catches. While there are fishery-specific considerations in terms of the transfer and extension of such modifications nationally, the concepts remain valid and should see similar benefits realised across different fisheries.

The second aim of this project was to identify an appropriate framework for developing future modifications. That goal has also been achieved. Ongoing work is now essential to refine modifications within the two identified areas of most benefit, and also to promote industry extension and adoption. Such strategic research will provide Australian prawn-trawling fisheries with a tool box of solutions to mitigate environmental concerns as they eventuate, and clearly should be a priority.

The third project aim was to assist local commercial fishers and managers to implement and, where appropriate, legislate key modifications. This work is ongoing, but permits have been sought by NSW fishers (from fisheries managers) to use some of the key modifications developed during the project, including multi-rigged otter and beam trawls and shorter trawls with smaller mesh in estuaries and alternative ground gears (including versions of the soft brush) in oceanic waters. Other voluntary trials/experiments are being undertaken with oceanic commercial fishers to further refine and test novel otter boards. It is anticipated that modified prawn trawls and their ongoing refinement will be a key component of new fisheries reforms.

# Implications

The ultimate implications of this work are a clear understanding of the utility and subsequent prioritisation of modifications to the configurations, otter boards, ground gear and netting structures of prawn trawls that maintain target catches while reducing bycatch, habitat impacts and inefficiencies.  Implicit aspects of these outcomes are improved environmental and economic viability, not only for prawn-trawl fisheries in NSW, but throughout Australia.  This means that the beneficiaries of the research outputs will not only include Australian prawn-trawl fisheries, but all other interacting fisheries (including commercial and recreational) that target the various bycatch species.  These fisheries and their stakeholders will all benefit from lower risk of deleterious impacts and therefore enhanced resource sustainability.

Any ancillary reductions in fuel usage by Australian prawn trawlers have obvious benefits to the broader population (through lower carbon emissions), although the greatest impacts will be to individual operators and their local fisheries in terms of improved profitability.  Specifically, the benefits of the proposed outcomes can be measured as increased eco-efficiency, which directly manifests as improved financial returns per kg of prawns harvested.

Beyond increasing the viability of prawn trawling in Australia, the results have provided a robust base from which gear technologists and industries can now direct future efforts to improve profitability and mitigate associated environmental impacts.  Also, because immediate solutions (e.g. optimising mesh size) have been identified for NSW estuarine prawn-trawl fisheries, fisheries managers and management advisory committees will be able to use the information to design and apply appropriate industry-development programs.  The recognition and refinement of such gear-based solutions will have significant long-term benefits to the trawling industry and all users of resources impacted by prawn-trawling operations.

# Recommendations

While there has been extensive experimental testing of modifications in NSW, including the issuing of permits for commercial use across broad temporal and spatial scales, additional funding should now be provided to refine modifications within the identified key zones and promote national adoption and extension. There are key sustainability issues and environmental targets existing in prawn fisheries across Australia, such as reducing the bycatch of giant cuttlefish in Spencer Gulf, or a necessary 30% reduction in total bycatch in the Northern Prawn Fishery, that could be addressed via the development framework and the underlying concepts and successful modifications identified in this project.

## Further development

The research project has isolated the key areas of prawn-trawling systems that could be modified to improve efficiencies and a framework for ongoing research. Specifically, it is clear that the spreading mechanisms and the trawl bodies (including the mesh size, orientation and type) offer the greatest utility for future development. There is now a clear need to (1) develop innovative, high-priority technological modifications to these components that mitigate sustainability issues (something that has not been done) and (2) promote their adoption among industries through dedicated extension activities.

It is not unrealistic to expect that some simple modifications to existing configurations could translate to individual fuel savings of >30% for an operator and at the same time significantly reduce unwanted bycatches of key species by more than 90%. The combined realisation of such outcomes would have extremely positive benefits for, not only NSW prawn-trawling industries, but those nationally as well.

Given the above, we recommend that future studies develop, refine and extend (among Australian fisheries) modifications to the spreading mechanisms and bodies of prawn trawls that concomitantly reduce their fuel intensities, bycatch and habitat impacts (thereby holistically addressing environmental deficiencies) while maintaining target catches. As per Figure 7, such modifications encompass: exploring the potential for (1) higher-order multi-trawl systems, (2) installing SAFEs between spreading mechanisms, (3) retroactively fitted modifications to existing otter boards and new designs for reducing the AOA, (4) increasing lateral mesh openings at strategic positions in the trawl body via square-mesh panels or T90, and (5) minimising twine areas via alternative trawls designs. Ultimately, this work will contribute towards improving the social and economic return of local prawn-trawl fisheries, while helping to ensure their ongoing sustainability.

# Extension and adoption

The main outputs from this project were (1) the identification and prioritisation of the most effective suites of modifications to the anterior sections of prawn trawls that reduce their bycatch, drag and habitat impacts, while improving their profitability, (2) detailed information on the mechanisms of action of such priority modifications, so that (3) a clear direction could be proposed for the future development of more eco-efficient gears throughout Australian prawn-trawl fisheries. These outputs were extended using existing networks developed during previous, related projects. The dissemination, extension and adoption plan was as follows:

## Extension and adoption plan objectives:

(1) Encourage the participation of NSW and other Australian prawn-trawl fisheries in the development, application and testing of appropriate anterior gear modifications that reduce the bycatch, fuel consumption and habitat impacts of prawn trawls, while improving their profitability.

(2) Ensure that all prawn-trawl fishers, support networks (e.g. fishers' cooperatives, net makers, etc.) and other key stakeholder groups, including state and federal agencies and international NGOs are aware of the research outcomes;

(3) Promote a framework for future research among scientists and industries of the most appropriate suite of anterior modifications to prawn trawls.

(4) Promote the adoption of any recommended modifications.

These objectives were achieved according to the following plan:

(1) Target audience: Commercial fishers and support networks.

Key messages: The needs and benefits of the research outcomes for industry, in terms of ecological, economic, social, and legal aspects, the research process and ongoing outcomes (recommended modifications) of completed experiments and the framework for the future development of anterior gear modifications to prawn trawls.

Communication/extension methods: The above key messages were extended during regular port meetings, workshops, MAC and advisory council meetings, and as part of letters, articles in industry publications and research summaries during the project (appendices 20–24). We used photos collected during field work to produce slide shows summarising the results of the project. Once experiments were completed, summaries were distributed to individual fishers and other relevant stakeholders.

Commercial prawn fishers have requested permits from managers to trial some of the modifications developed during the project. Other fishers have volunteered their vessels to allow us to demonstrate the utility of several modifications, including novel otter boards and trawl-body modifications (e.g. square-mesh side panels). This work is ongoing.

(2) Target audience: Key stakeholder groups and the general public.

Key message: An initial project brief, and then six-monthly non-technical summaries of research results.

Communication/extension: Web summaries, magazine articles and media releases were used to disseminate summaries to other stakeholder groups and the general public. We created various forms of media summarising the results of the work that were distributed to other stakeholders and the general public (Appendix 24).

(3) Target audience: Fisheries managers.

Key message: Ongoing outcomes of the research and the recommended progression of modifications.

Communication/extension: Fisheries managers were briefed throughout the project via email, non-technical summaries and meetings. Both local and national industries and fisheries managers were already well aware of the need to implement changes to prawn trawls to reduce their environmental foot print and increase their profitability, and so it is likely that like previous, related research projects, the results from this project will be incorporated into plans for the ongoing testing and eventual legislation of modifications.

The key messages were disseminated in accord with the milestones for the project. All results have been published and/or disseminated. The success of the extension plan can be measured by the level of industry participation in the research and the ongoing, voluntary adoption of recommended modifications. The latter currently is being facilitated through industry requests for permits to trial key modifications.

(4) Target audience: International scientific community.

Key message: The aims, methodologies and results of experiments.

Extension methods: Like all previous FRDC projects completed by the PI, numerous scientific papers were published in international journals. This has provided the necessary peer-reviewed scientific scrutiny of the research outcomes, thereby facilitating their eventual implementation through management processes.

## Project coverage

The project coverage is detailed in appendices 3−24.

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# Project materials developed

In total, 19 scientific papers, three magazine articles, a conference proceeding and 16 one-page industry summaries were produced describing the results of various innovative and novel modifications to the anterior sections of prawn trawls designed to address the stated objectives. From this work we have developed simple modifications for existing trawls (including the SAFE and square-mesh wing panels), and progressed a completely new design of tongue trawl (the W trawl), otter board and ground-gear modifications.

## **Appendix 1**. Intellectual property

The intellectual property owned by FRDC as specified in the agreed contract is 80%, although no specific commercial value was derived in terms of patents or copyrights.

## **Appendix 2.** Staff

Staff that worked on the project using funds from NSW DPI:
Craig Brand
Matt Broadhurst
Matthew Harrison

Staff that worked on the project using funds from the FRDC:
Chris Barnes
Mitch Burns
Matthew Harrison
Liz Hanna
Matthew McHugh
Jen Marshall
Russell Millar
Shiori Naga
Nick Sarapuk
Dave Sterling

Staff that worked on the project using funds from other sources:
Donald Anderson
Brian Cullis
Barry Johnson
Brian Johnson
Donald Johnson
Geoffrey Johnson
Steve Kennelly
Greg Skilleter
Graham Williams

**Appendix 3.** Broadhurst, M.K., Sterling, D.J. and Cullis, B.R. 2012. Effects of otter boards on catches of an Australian penaeid trawl. Fish. Res. 131–133: 67–75.

Fisheries Research 131–133 (2012) 67–75

Contents lists available at SciVerse ScienceDirect

Fisheries Research

journal homepage: www.elsevier.com/locate/fishres

# Effects of otter boards on catches of an Australian penaeid trawl

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ARTICLE INFO

*Article history:*
Received 11 May 2012
Received in revised form 10 July 2012
Accepted 15 July 2012

*Keywords:*
Beam trawl
Drag
Otter boards
Penaeids
Trawl efficiency

ABSTRACT

The effects of otter boards on the catches of *Metapenaeus macleayi* were quantified within the broad aim of promoting more hydrodynamic and environmentally benign trawl-spreading mechanisms. Two identical trawls (7.26 m footropes) were attached to 2.89-m sweeps and simultaneously fished in a double-rig; each alternately attached to either two otter boards or a rigid 6.0-m beam with parallel sleds (configured not to impact on the behaviour of *M. macleayi*). Both trawl configurations had the same total weight (143 kg) and initial wing-end spreads (predicted means of 4.33 and 4.45 m), although the otter boards caused significantly more variable wing-end spread during towing. Replacing the otter boards with the beam significantly reduced system drag (by 10%) and the weights and numbers of school prawns per hectare swept by the footropes (by 33%); with the latter attributed to the concomitant reduction in lateral bottom contact of the system. Standardised catches of the most abundant teleost *Herklotsichthys castelnaui* were also significantly lower (by 79%) in the beam trawl. The results support the potential for compensatory adjustments to penaeid-trawl parameters (e.g. footrope length) to offset reductions in the bottom contact of spreading mechanisms that are modified to minimise drag and/or habitat impacts.


## 1. Introduction

Penaeids form the basis of important fisheries throughout the world's tropical and temperate coastal regions (Vendeville, 1990; Gillett, 2008). Approximately 110 species are harvested using various stationary and mobile demersal gears; many of which historically have raised concerns owing to (i) their often poor species selection (and associated large unaccounted fishing mortalities; Broadhurst et al., 2006); and, for mobile gears, their (ii) habitat impacts (Burridge et al., 2003); and (iii) intensive use of fossil fuels (Suuronen et al., 2012). Over the past 30 years, the first issue has been extensively addressed for many gears, mostly via modifications to the posterior sections to include either bycatch reduction devices (BRDs), or more consistent lateral mesh openings (see Broadhurst, 2000 for a review). Comparatively fewer technological solutions have been developed to address the remaining two concerns (habitat impacts and efficiencies) of mobile gears, but their resolution is considered a priority for the sustainability of many fisheries (He and Winger, 2010; Suuronen et al., 2012).

There are various mobile penaeid fishing gears, including pushed 'skimmer' or 'butterfly' nets (e.g. Hein and Meier, 1995) and encircling or towed seines (e.g. Macbeth et al., 2005), but by far the most common gears are trawls; which also evoke the greatest perceived environmental concerns (Vendeville, 1990; Gillett, 2008). Although the basic fishing mechanism remains the same (i.e. to physically stimulate benthic-dwelling penaeids from the substratum and into the trawl), the configurations and operations of penaeid trawls vary considerably. In some fisheries, single nets are horizontally spread between two vessels fishing in parallel (i.e. pair trawl; Vendeville, 1990), but most are deployed in multi-gear configurations (termed double-, triple- and quad-rigs); sometimes posterior to a rigid beam between two parallel sleds (beam trawl), although more typically using hydro vanes (termed otter boards) (Gillett, 2008). Because these latter two spreading mechanisms comprise a substantial weight of any given trawling system, their modification provides a good starting point for addressing fuel inefficiencies and habitat impacts. This is especially the case for otter boards, which operate at 30–45° to the tow direction (sweeping a path on the substrate with a width of 50–70% of their length) and can account for up to 40% of the total drag of some configurations (Sterling, 2000; Sterling and Eayrs, 2010). Equally important, otter boards tend to penetrate the substratum more than any other trawl-gear component (e.g. Gilkinson et al., 1998).

There are several options for improving the efficiencies and/or reducing the bottom contact of otter boards. Modifications include: (i) subtle re-configurations of existing designs involving lower angles of attack, greater aspect ratios (He and Winger, 2010), and possibly sleds/wheels fitted to the base plate (Kennelly and

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http://dx.doi.org/10.1016/j.fishres.2012.07.015

Broadhurst, 2002); or (ii) completely new designs, such as the 'batwing door' which, like a sled on a beam, is towed parallel to the vessel (Sterling and Eayrs, 2010). Alternatively, in some small-scale, shallow-water fisheries, it may be feasible to simply replace otter boards with a beam assembly, and so reduce bottom contact to the width of the sled's base plates.

However, one important consideration associated with modifying (or removing) otter boards is that they (i) often represent a considerable percentage of the trawl bottom contact and (ii) (unlike sleds) are angled to direct water flow towards the trawl mouth. These factors are likely to affect the catches of penaeids which remain on, or more commonly buried in, the substratum (Ruello, 1973; Coles, 1979; Wassenberg and Hill, 1994). The potential for such impacts has not been extensively investigated, but is important since, to encourage adoption of more hydrodynamic and environmentally benign spreading mechanisms by fishing industries, there may be some justified requirement for compensatory adjustments to other gear parameters in order to maintain target catches.

We sought to investigate this issue in the Clarence River penaeid-trawl fishery in New South Wales (NSW), Australia. Currently, up to 93 operators tow double-rig trawls (each with a headline <7.35 m) from small vessels (<10-m and 110-kW) to target *Metapenaeus macleayi*. Catches can exceed 400 mt per annum, and are valued at almost $A 3 million. Like in many overseas trawl fisheries (e.g. Sala et al., 2008; Priour, 2009), rising fuel costs have led to recent efforts in this fishery to develop more efficient trawling systems. To contribute to this momentum and promote refinements to spreading mechanisms, our main aim in this study was to determine the potential for an effect of conventional otter boards on the catches of *M. macleayi*. This was done by simultaneously comparing identical penaeid trawls (i.e. the same headline length, ground rigging, tapers, mesh size, etc.); one with otter boards attached to the sweeps (2.89 m), and the other with the otter boards removed and replaced by a beam assembly that was engineered to avoid stimulating responses from *M. macleayi*; based on their known behaviour (Ruello, 1973; Coles, 1979; Broadhurst, 2000). A subsidiary aim was to assess the potential utility (in terms of engineering and catching performance) of the beam as an alternative spreading mechanism in this fishery.

## 2. Materials and methods

### 2.1. Equipment used

The experiment was done during October 2011 using a local trawler (10 m long and powered by a 104 kW engine) in Lake Wooloweyah (29°26′S 153°22′E), which is a shallow (<2 m) coastal lagoon (reasonably flat sand and mud substratum) close to the mouth of the Clarence River, and an important location for the trawl fishery (i.e. responsible for >35% of the total annual catch). The trawler had two separate hydraulic winches attached to 8-mm diameter (Ø) stainless-steel bridles that were directed laterally and aft through pulleys on two booms (each 5 m long) located amidships. Electronic equipment included a global positioning system (GPS; Lowrance) to record the distance trawled, fuel monitor (Floscan series 9000), and attachable load cells (Amalgamated Instrument Company; model no. PA6139) to measure the combined tension in the bridles on each side. The load cells were linked to a data logger (Amalgamated Instrument Company; model no. TP4).

Two identical, labelled trawls were constructed from 40-mm mesh (1.5-mm Ø twisted polyethylene twine) and rigged with Nordmøre-grids (20-mm bar spaces) and square-mesh codends comprising 27-mm polyamide mesh (2.25-mm Ø braided twine) hung on the bar (Figs. 1 and 2). The headlines and footropes of both trawls had netting attached along 7.26 m of their total 7.70 m lengths (Fig. 1). The wing-ends were attached to three 2.89-m sweeps; the anterior ends of which could be clipped to either (i) two cambered-steel otter boards (1.07 m long × 0.76 m high, with 100-mm base plates and 54 kg in air), or (ii) a steel beam assembly (Fig. 2). The total weight of each configuration (trawl, sweeps and spreading mechanism) was 143 kg (in air).

The beam assembly comprised two sleds (0.76 m high, with 75-mm base plates) that were located beneath opposite ends of a horizontal, rectangular steel bar (40 mm deep × 100 mm wide × 6 m long) (Fig. 2b). The length of the steel bar was chosen to match the anticipated spread of the otter boards, and to ensure that the sled's base plates were located well outside the mouth of the trawl (Fig. 2b and c). Further, the horizontal bar was located within 200 mm of the upper sweep towing point, to ensure that it would transverse the water column at a similar height to the trawl headline, and well above the location of *M. macleayi* in the substratum (Ruello, 1973; Coles, 1979).

### 2.2. Experimental design and analyses

Prior to starting the experiment, the inside openings of 20 random meshes were measured (using a local, purpose-built mesh gauge) in each trawl. At the start of each fishing day, the beam and otter boards were alternately shackled to the bridles on either side of the vessel, and also clipped to the trawls (via the sweeps). Between three and eight paired 40-min deployments were done on each of nine days of fishing, with the two trawls alternated between the sides of the vessel once within each day. This system ensured that similar numbers of deployments were done with both trawls attached to the otter boards and beam, and on either side of the vessel. The configurations were always deployed with 9.5 m of bridle (from the boom end) and towed at 1.3–1.5 m $s^{-1}$, according to conventional operations in this fishery.

Various technical and biological data were collected for each deployment. Immediately after the trawls were deployed, the load cells were attached to the bridles and used to continuously measure the drag (kgf), which was logged as averages over 1-min intervals. The horizontal opening of each trawl was recorded by securing vertical 2.4-m timber poles (23-mm Ø) to all four trawl wing-ends (Fig. 2a and b). Each pole was marked in horizontal red and white sections (200 mm) and protruded from the surface of the water during fishing (Fig. 2a and b). Within 10 min of the start and prior to the end of each deployment, two replicate photographs of the poles were taken as close as possible to perpendicular to the trawls (from the boom ends). The photographs were subsequently analysed to calculate wing-end spread based on the known geometry of the gear (i.e. height and distance of subject and length of poles). This technique was validated by recreating the vessel-and-trawl geometry on land and performing nine replicate measures, with an accuracy of 98.2 ± 0.16%. The distance trawled and fuel used per deployment were recorded using the plotter and fuel monitor, respectively. The fuel used for each gear was apportioned based on the relative measured tension in the towing wires.

At the end of each deployment, catches were separated by codend, and data collected on the total weights of *M. macleayi* and bycatch, the numbers of each bycatch species, and total lengths (TL to the nearest 0.5 cm) of the most abundant teleosts. Random samples of ~500 g of *M. macleayi* from each trawl and deployment were placed into plastic bags and transferred to the laboratory, where ~100 randomly selected prawns from each deployment were measured (carapace length – CL to the nearest 1 mm), weighed and counted. The latter data were used to calculate the numbers and mean sizes per deployment.

The hypothesis of no differences in mesh sizes between the two trawls was tested using a linear model (LM). The remaining

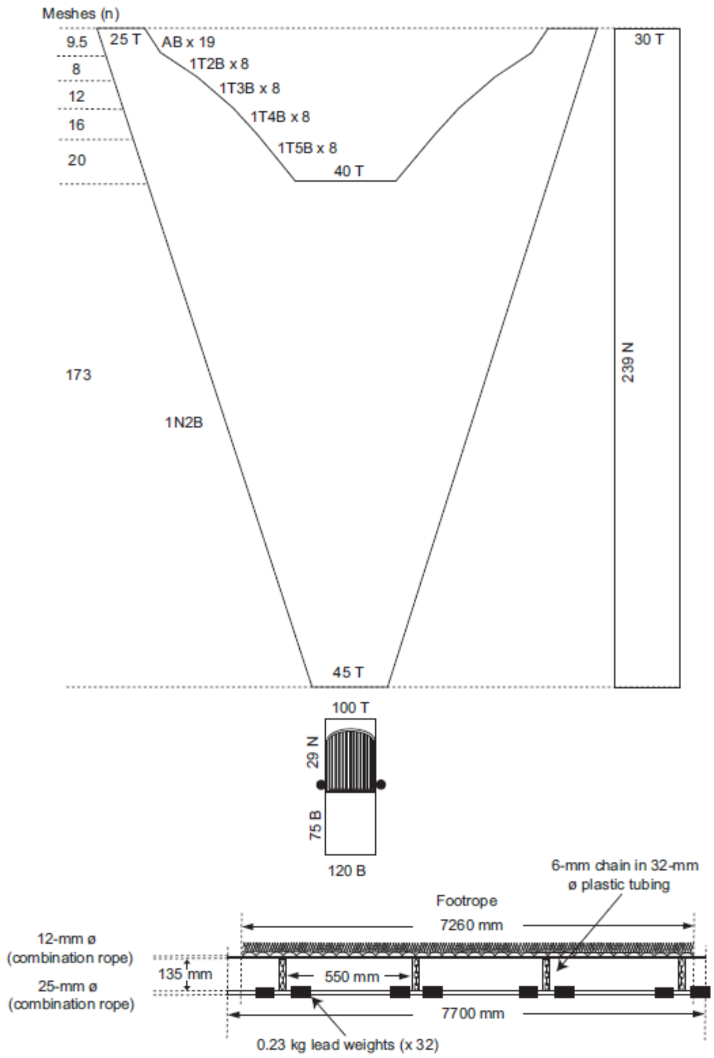
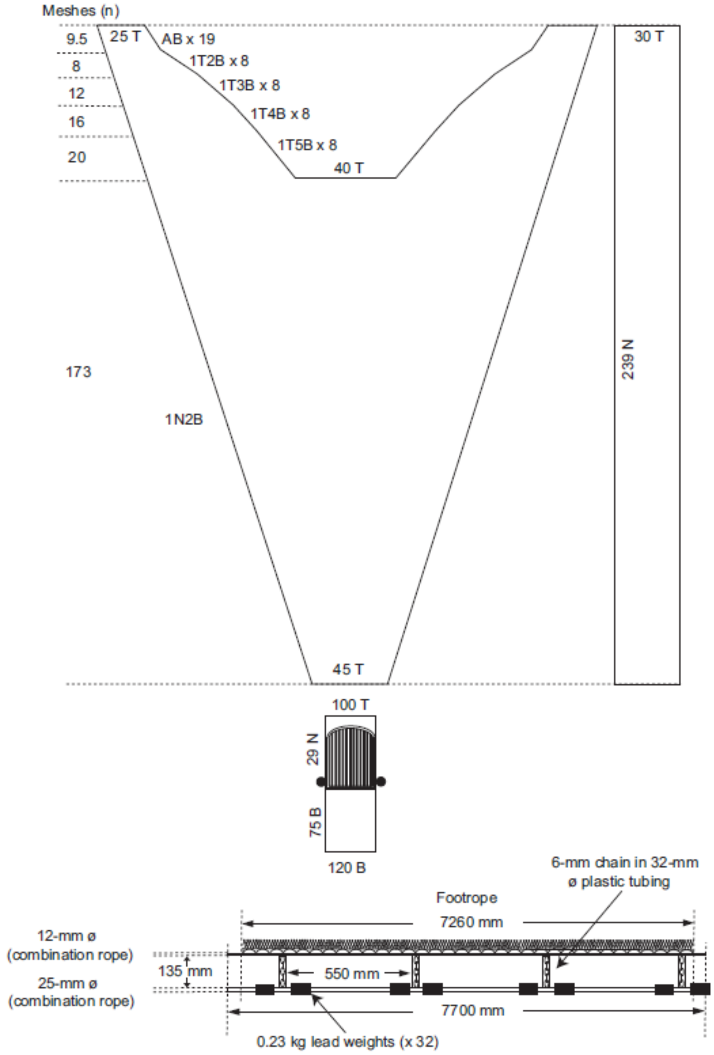



**Fig. 1.** Schematic diagram of the trawls used. N, normals; T, transversals; B, bars; and Ø, diameter.

biological and technical data collected during fishing were analysed to test the general assumption of no differences between spreading mechanisms, but in different formats. For each deployment, the numbers and weights of catches in the beam and otter trawls were standardised to hectare trawled using the swept area of the footrope (i.e. average wing-end spread × the distance trawled). Additionally, for the otter trawl, catches were also standardised to the swept area of the total system ((i.e. wing-end spread + span of otter-board contact) × the distance trawled), where the span of each otter-board contact was calculated at 0.55 m (or 1.1 m for both otter boards) by multiplying the otter-board length (1.07 m) by the sine of the angle of attack (31° – calculated from the predicted wing-end spread and using the model proposed by Sterling, 2000). Because the relatively thin sled-base plates of the beam trawl were outside the wing-ends and in line with the direction of towing, for this configuration (Fig. 2c), the footrope and total-system swept areas were considered to be the same.

All standardised catch data using (i) the footrope and (ii) total-system swept areas of the two trawl configurations were then log-transformed to account for an assumed multiplicative relationship with causal factors and analysed in two separate linear mixed models (LMMs). Data for the wing-end spread at the start of trawling, subsequent change in wing-end spread at the end of trawling, mean CL of *M. macleayi* and replicate drag per deployment were analysed in their raw format in separate LMMs.

All LMMs included 'spreading mechanism' as the only fixed term. Random terms comprised various main effects and interactions (including some for spreading mechanism) between 'trawls'

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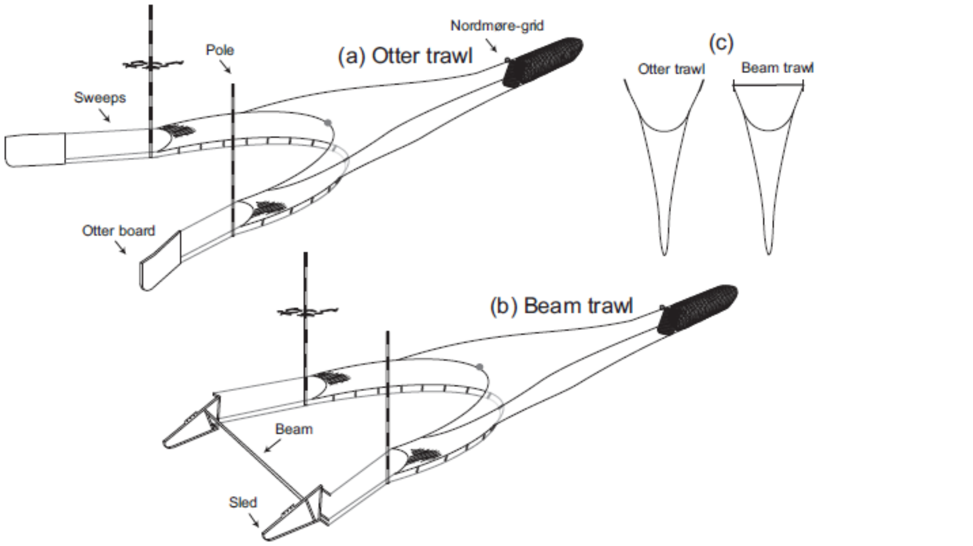


**Fig. 2.** Three-dimensional view of the (a) otter and (b) beam trawls with vertical poles attached at the wing ends, and (c) two-dimensional view of both configurations during deployment.

(two levels), 'sides' of vessel (two levels), 'days' (nine levels), 'deployments' (up to eight levels for each day) and an additional term called 'haul plot' which defined the 'plot' stratum for the trawl factor within each day (trawls were alternated every 3–4 hauls within a day). The LMM for drag also included additional terms for the 'load cell' (two levels) and the residual term within day, haul and side to account for the multiple (but unequal) measurements within each day × deployment × side combination.

All data were modelled with and without realised covariances to test for variance heterogeneity, with the most appropriate model chosen using a likelihood ratio test. The LMMs were fitted in ASReml-R (Butler et al., 2009), and the significance of the spread system determined using a Wald *F*-test. Size–frequency data for key fish were pooled, plotted and graphed.

## 3. Results

Both trawls had virtually identical mesh sizes (mean ± SE of 40.22 ± 0.23 mm and 40.28 ± 0.23 mm; LM, Wald $F = 0.024$; $p > 0.05$). Fifty-one paired deployments were completed, during which there was no significant difference in the initial trawl wing-end spreads achieved by the beam and the otter boards (predicted means of 4.45 and 4.33 m; LMM, $p > 0.05$; Table 2; Fig. 3a and b). However, compared to the beam, the otter board had significantly more variable wing-end spread at the end of the deployments (LMM, $p < 0.001$; Table 2; Fig. 3c and d). The trawled distances during each deployment remained very similar (3344.6 ± 16.9 m), while average (±SE) towing speed and fuel consumption per paired deployment were 1.39 ± 0.007 m s$^{-1}$ and 8.55 ± 0.12 L, respectively.

The total catch was 942 kg; most of which (93%) comprised *M. macleayi* (Table 1). Eight teleosts were responsible for >85% of the bycatch by number, including: *Herklotsichthys castelnaui* (22%); *Pomatomus saltatrix* (19%); *Ambassis marianus* (12%); *Gerres subfasciatus* (11%); *Acanthopagrus australis* (9%); *Rhabdosargus sarba* (8%); *Ambassis jacksoniensis* (7%); and *Siphamia roseigaster* (7%) (Table 1). Analyses of biological data were limited to these species.

**Table 1**
Scientific and common names and abundances of organisms caught during the experiment.

| Family | Scientific name | Common name | Catch |
|---|---|---|---|
| *Crustaceans* | | | |
| Penaeidae | *Metapenaeus macleayi* | School prawn | 879 |
| Palaemonidae | *Macrobrachium* sp. | Freshwater prawn | 1 |
| *Molluscs* | | | |
| Loliginidae | *Uroteuthis* sp. | Squid | 8 |
| *Teleosts* | | | |
| Ambassidae | *Ambassis jacksoniensis* | Port Jackson glassfish | 455 |
| | *Ambassis marianus* | Ramsey's perchlet | 804 |
| Apogonidae | *Siphamia roseigaster* | Pink-breasted siphonfish | 423 |
| Clupeidae | *Herklotsichthys castelnaui* | Southern herring | 1413 |
| | *Hyperlophus vittatus* | Whitebait | 3 |
| Eleotrinae | *Gobiomorphus australis* | Striped gudgeon | 1 |
| Engraulidae | *Engraulis australis* | Australian anchovy | 15 |
| Gerreidae | *Gerres subfasciatus* | Silver biddy | 707 |
| Gobiidae | *Arenigobius bifrenatus* | Bridled goby | 8 |
| Haemulidae | *Pomadasys kaakan* | Javelin fish | 2 |
| Hemiramphidae | *Arrhamphus sclerolepis* | Snubnose garfish | 4 |
| | *Hyporhamphus regularis* | River garfish | 10 |
| Lutjanidae | *Lutjanus russelli* | Moses perch | 1 |
| Megalopidae | *Megalops cyprinoides* | Oxeye herring | 1 |
| Monodactylidae | *Monodactylus argenteus* | Diamond fish | 1 |
| Mugilidae | *Mugil cephalus* | Bully mullet | 32 |
| | *Liza argentea* | Flat-tail mullet | 13 |
| Paralichthyidae | *Pseudorhombus arsius* | Largetooth flounder | 97 |
| Platycephalidae | *Platycephalus fuscus* | Dusky flathead | 46 |
| Plotosidae | *Euristhmus lepturus* | Longtail catfish | 28 |
| Pomatomidae | *Pomatomus saltatrix* | Tailor | 1243 |
| Sciaenidae | *Argyrosomus japonicus* | Mulloway | 3 |
| Sillaginidae | *Sillago ciliata* | Sand whiting | 21 |
| Sparidae | *Acanthopagrus australis* | Yellowfin bream | 563 |
| | *Pagrus auratus* | Snapper | 5 |
| | *Rhabdosargus sarba* | Tarwhine | 489 |
| Terapontidae | *Pelates quadrilineatus* | Trumpeter | 1 |
| Tetraodontidae | *Tetractenos glaber* | Toadfish | 42 |

All data are numbers, except *M. macleayi* (kg).

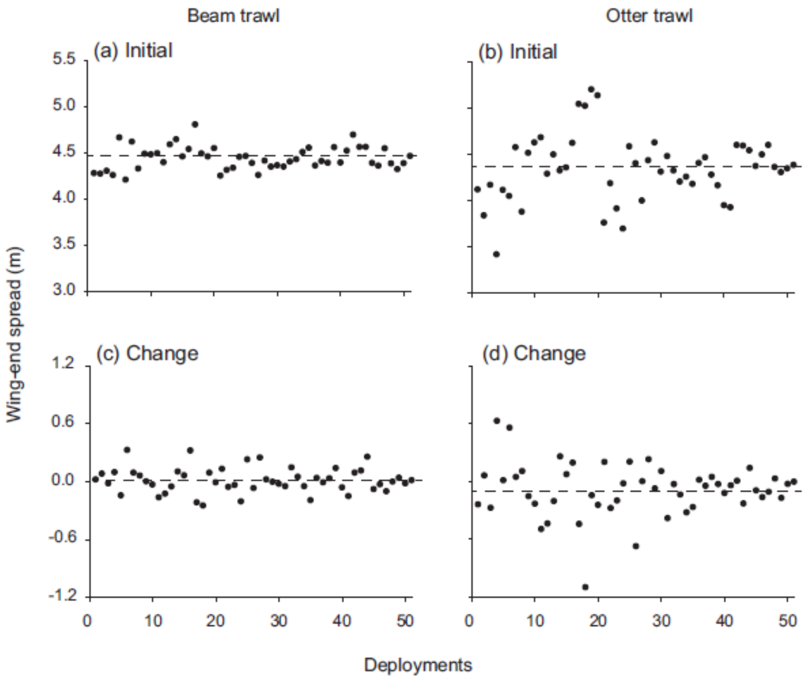


**Fig. 3.** Scatter plots of the initial and subsequent changes (final–initial) in wing-end spreads for each paired deployment of the beam (a and c) and otter (b and d) trawls. Horizontal dashed lines depict predicted means from linear mixed models.

There was a significant effect of spreading mechanism on the weights and numbers of *M. macleayi* per hectare of footrope swept area, with predicted means that were both 33% lower in the beam than otter trawl (LMM, $p < 0.001$; Table 2; Fig. 4a and b). A significant difference was maintained between the beam and otter trawl for the weights of *M. macleayi* per hectare of total-system swept area (LMM, $p < 0.001$; Table 2; Fig. 4a), but not their numbers – although the predicted mean reductions for both variables were similar (~16%; LMM, $p > 0.05$; Table 2; Fig. 4b). Compared to the otter trawl, the beam trawl also retained significantly fewer *H. castelnaui* per hectare for both footrope and total-system swept areas (by 79 and 74%) (LMM, $p < 0.001$; Table 2; Fig. 4e). Irrespective of the footrope or total-system swept area, spreading mechanism had no significant effect on the numbers and weights of total bycatch, and numbers of *P. saltatrix*, *A. marianus*, *G. subfasciatus*, *A. australis*, *R. sarba*, *A. jacksoniensis* or *S. roseigaster* (LMM, $p > 0.05$; Table 2, Fig. 4c, d and f–l). However, for many species and the total bycatch, there were fewer catches per hectare of footrope swept area in the beam trawl, but comparable catches per hectare between spreading mechanisms for total-system swept area (Fig. 4).

There was no significant difference in the predicted mean CL of *M. macleayi* between the beam (14.29 mm CL) and otter trawls (14.14 mm CL) (LMM, $p > 0.05$; Table 2; Fig. 5a). Further, the pooled size–frequency distributions of the key teleosts (all <20 cm TL) revealed similar patterns among individuals caught in the beam and otter trawls, except for tailor; proportionally larger sizes of which were retained in the trawls attached to the otter boards than in the beam (Fig. 5c).

Drag was significantly affected by spreading mechanism (LMM, $p < 0.001$; Table 1). Under the conditions examined, mean predicted

**Table 2**
Summary of Wald *F* from linear mixed models assessing the importance of the fixed effect of spread mechanism in explaining the variability in engineering performances and catches of key organisms by the trawls.

| Raw variables | | Wald *F* |
|---|---|---|
| Initial wing-end spread | | 0.72 |
| Change in wing-end spread at the end of the deployment | | $11.12^{***}$ |
| Drag | | $57.34^{***}$ |
| Mean CL of *M. macleayi* | | 2.38 |
| Transformed variables (log catches per hectare) | Wald *F* | |
| | Footrope swept area | Total-system swept area |
| Wt of *M. macleayi* | $70.07^{***}$ | $11.26^{*}$ |
| No. of *M. macleayi* | $25.71^{*}$ | 4.45 |
| Wt of total bycatch | 4.21 | 1.90 |
| No. of total bycatch | 2.65 | 0.81 |
| No. of *Herklotsichthys castelnaui* | $55.15^{***}$ | $41.93^{***}$ |
| No. of *Pomatomus saltatrix* | 1.99 | 0.71 |
| No. of *Ambassis marianus* | 0.27 | 0.87 |
| No. of *Gerres subfasciatus* | 0.11 | 0.00 |
| No. of *Acanthopagrus australis* | 0.06 | 0.01 |
| No. of *Rhabdosargus sarba* | 3.69 | 1.60 |
| No. of *Ambassis jacksoniensis* | 0.71 | 0.05 |
| No. of *Siphamia roseigaster* | 1.01 | 0.02 |

Engineering data and the mean carapace length (CL) of *Metapenaeus macleayi* were analysed in their raw form. Catches were first standardised to per hectare, calculated using both the (i) footrope swept area (average wing-end spread) and (ii) total-system swept area (average wing-end spread + otter boards) of the trawls and then log-transformed.
$^{*}$ $p < 0.05$.
$^{***}$ $p < 0.001$

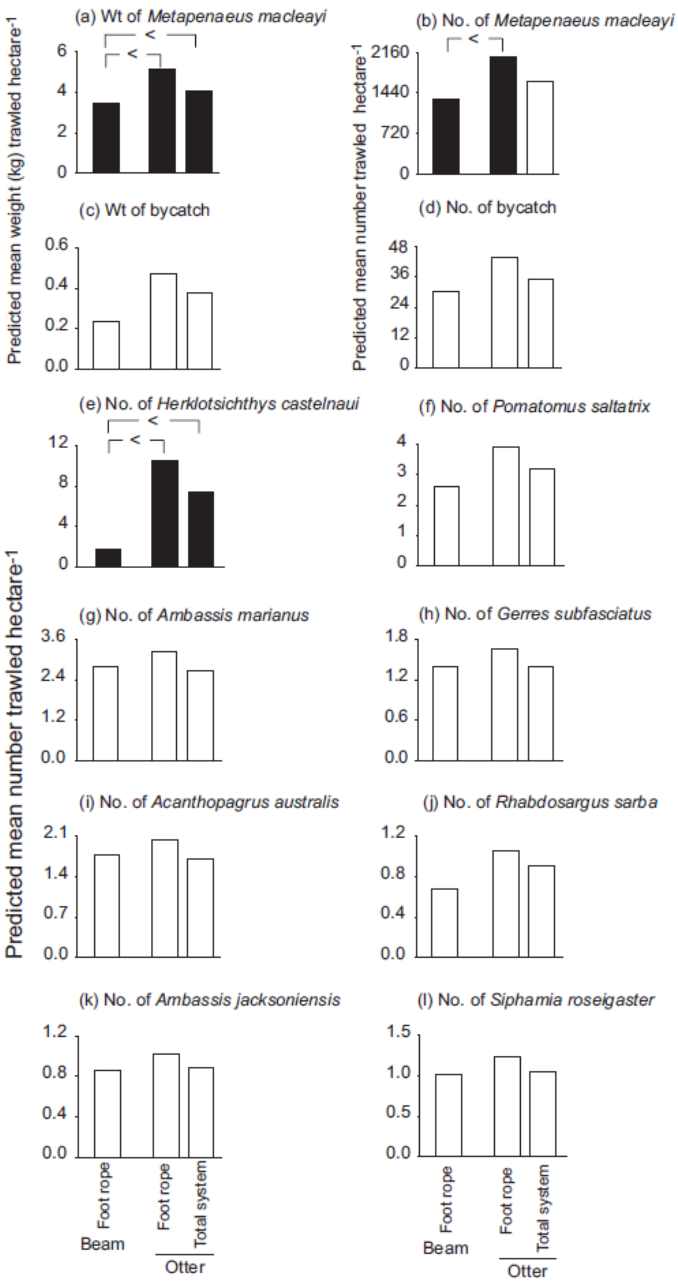


**Fig. 4.** Differences in predicted mean back-transformed catches per hectare between the beam trawl (swept area of the footrope only) and otter trawl (swept area of the footrope only and also the footrope and otter boards combined – 'total system'): (a) weights and (b) numbers of *Metapenaeus macleayi*, (c) weights and (d) numbers of bycatch, and numbers of (e) *Herklotsichthys castelnaui*, (f) *Pomatomus saltatrix*, (g) *Ambassis marianus*, (h) *Gerres subfasciatus*, (i) *Acanthopagrus australis*, (j) *Rhabdosargus sarba*, (k) *Ambassis jacksoniensis*, and (l) *Siphamia roseigaster*. Shaded histograms represent significant Wald *F*-values detected in linear mixed models, while < shows the direction of differences.

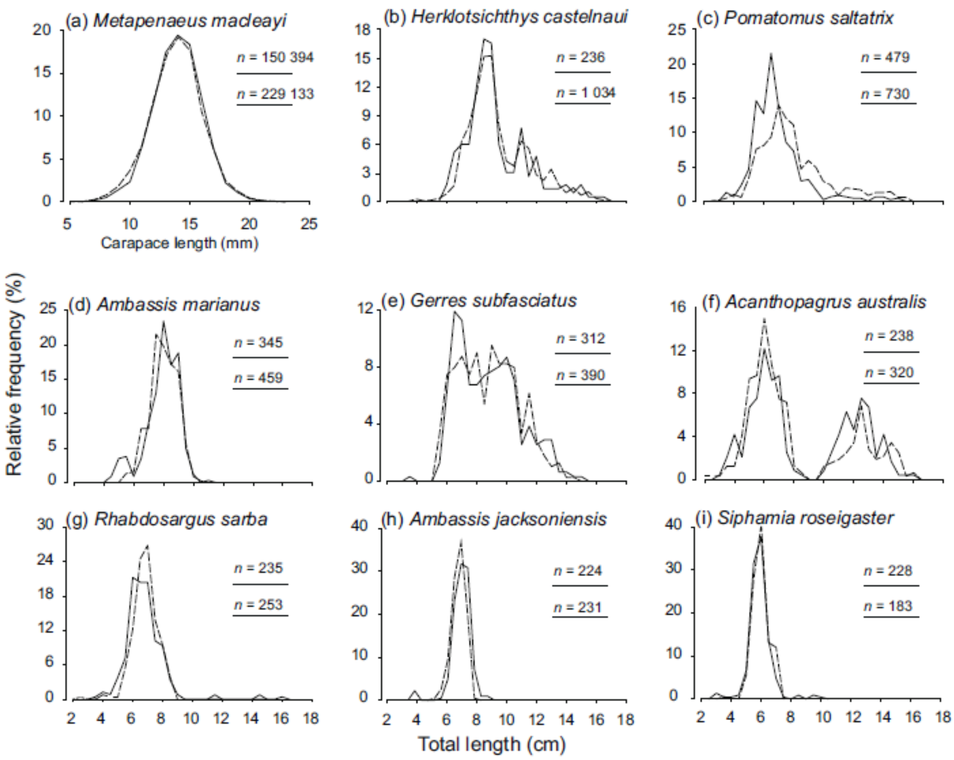


**Fig. 5.** Size–frequency distributions between the beam (solid lines) and otter trawl (broken lines) for (a) *Metapenaeus macleayi*, (b) *Herklotsichthys castelnaui*, (c) *Pomatomus saltatrix*, (d) *Ambassis marianus*, (e) *Gerres subfasciatus*, (f) *Acanthopagrus australis*, (g) *Rhabdosargus sarba*, (h) *Ambassis jacksoniensis*, and (i) *Siphamia roseigaster*. Horizontal axis is total length in cm except in (a).

drags were 254.53 and 282.84 kgf for the beam and otter trawls, respectively. In terms of fuel usage, this equated to averages of 4.05 and 4.50 L per 40-min deployment.

## 4. Discussion

The data from this study support the supposition that otter boards affect the catches of *M. macleayi* in Clarence River trawls. Before discussing the implications of these results in terms of refining penaeid-trawl spreading mechanisms, it is necessary to adequately assign and justify causality, which can be done by comparing the known and likely (i) geometries of the trawls attached to each spreading mechanism and also (ii) the behaviour of the key species.

To achieve comparable wing-end spreads, we chose a beam length (6 m) based on the estimated otter-board spread during conventional fishing in Lake Wooloweyah. Although the otter boards caused considerably more variable wing-end spread than the beam during towing, the predicted initial spreads of each system were not significantly different (i.e. means varied by only ~12 cm or ~2.5%). Beyond variations in footrope swept area (and therefore catches – which were adjusted in the LMMs), it is unlikely that the observed differences in wing-end spread greatly affected trawl geometry, including the angles and lateral openings of meshes. Vertical trawl openings similarly would have remained consistent between systems, since this was determined at the otter board and beam sled height of 0.73 m and by the same fixed height of the poles attached at the wing ends of both trawl systems. A related, potentially confounding issue is that, because the otter boards were independent of each other, their trawl might have more closely followed bottom contours and maintained better footrope contact than that attached to the rigid beam. However, this is unlikely because (i) the bottom was mostly flat and soft, and (ii) since there was no observed vertical displacement of the poles, the sweeps were probably long enough to absorb any vertical movement of either spreading mechanism.

Another important consideration is validity of the assumption that the horizontal steel bar of the beam arrangement had no discernable impact on the subsequent capture of *M. macleayi* by the trawls. There are few studies describing penaeid reactions to towed gears, although similar to other crustaceans, and unlike fish, their behaviour is quite specific, with responses mostly evoked by tactile stimuli (Newland and Chapman, 1989; Watson, 1989). Specifically, Watson (1989) observed that penaeid responses to an approaching trawl were limited to contraction of the abdomen after strong external stimuli from contact with the ground chain and footrope. While no similar direct observations have been made for *M. macleayi* in trawls, like most penaeids, this species predominantly resides within the substratum (Ruello, 1973; Coles, 1979; Wassenberg and Hill, 1994). Also, the importance of tactile, rather than visual, stimuli, for affecting the capture of *M. macleayi* is reflected in (i) the configurations of conventional trawls, which have low headline heights and are specifically designed to maximise and maintain bottom contact along the ground chain and, more importantly (ii) their observed lack of any active response to highly visible barriers in trawls associated with BRDs like the Nordmøre-grid (Broadhurst, 2000). A thin horizontal beam passing well above the substratum would be unlikely to evoke any response from *M. macleayi*; a statement also supported by the commercial use of beam trawls (with larger horizontal bars) in other fisheries targeting *Metapenaeus* spp. (Gillett, 2008).

Assuming comparable trawl geometries and bottom contact and no confounding effects of the horizontal beam on *M. macleayi*, their greater catches in the otter trawl can be mostly attributed to the associated boards, which probably disturbed buried individuals and then deflected them towards the trawl opening. In contrast, because the sleds on the beam were located well beyond the wing-ends (e.g. each by ~85 cm), were relatively narrow (75 mm), and had no angle of attack, the number of disturbed *M. macleayi* would be relatively low, and these likely would have avoided capture.

It is also clear that the catching efficiency of the otter boards extended beyond their simple linear bottom contact (e.g. 0.55 m each). More specifically, if such a relationship existed, then adding the physical swept area of the otter boards to that of the footrope (to provide total system swept area) should have resulted in a non-significant Wald *F* for prawn catches per hectare between spreading mechanisms. While this occurred for the numbers of *M. macleayi*, the weights remained significantly different, indicating that the otter boards caught proportionally more biomass than would be expected from simply their swept area. An explanation for this result is that, owing to their much greater weight and therefore deeper penetration than the footrope, they probably contacted relatively more individual prawns. A similar concept underlies the use of 'teeth' in towed dredges to penetrate the substrate and improve catches of other benthic organisms (e.g. Gasper et al., 1999).

Although significantly fewer *H. castelnaui* were similarly retained in the beam trawl, the mechanisms causing this result may be somewhat different to that described above. Unlike the mostly buried *M. macleayi* (Ruello, 1973), some fish would have maintained a higher orientation in the water column, and a more sustained response to the spreading mechanisms; which was probably influenced by their schooling behaviour, abundance, size and associated swimming ability (Watson, 1989; He, 1993). Schooling *H. castelnaui* (which were among the largest fish caught) may have detected either the otter boards or their posteriorly disturbed sediment clouds and were then herded by the sweeps into the trawl (Wardle, 1983; Watson, 1989). Removing the otter boards might therefore account for some reduction in their numbers. However, it is equally likely that because the horizontal beam was positioned well above the substrate, some *H. castelnaui* may have detected its approach and had sufficient time to be collectively directed away (or over).

Notwithstanding species-specific differences in responses, the relatively lower catches of *M. macleayi* and the potential for some reduction in fish in the beam trawl have implications for developing more environmentally benign spreading mechanisms. Specifically, while there are likely to be considerable differences among fisheries, if the otter boards are replaced with a beam, or modified to have less bottom contact, either within an existing configuration, or via substituting double- or quad-rigs (which require four otter boards) to either triple-, dual- or single-rigs (two otter boards), then some adjustment to the footrope length of a trawl may be warranted in order to maintain target catches. This strategy is justifiable from an engineering perspective, because the footrope can be increased without substantially affecting drag, and has less bottom contact than the otter boards. Obviously the converse also holds true, whereby reconfiguring spreading mechanisms could effectively improve bottom swept area and therefore catches.

Second, beyond any need to adjust systems to compensate for shifts in bottom swept area, simply using a beam instead of otter boards could potentially offer a solution for reducing bycatch. If the horizontal beam was responsible for directing *H. castelnaui* away from the trawl, this might be increased (for other species as well) by rigging novel physical or visual obstructions, such as rope arrays (similar to those described by Kim and Whang, 2010) or even air bubbles (e.g. Stewart, 1981). In terms of minimising unaccounted fishing mortality, modifications that prevent unwanted organisms from entering penaeid trawls are considerably more appropriate than those facilitating escape from the codend (Broadhurst et al., 2006). The same broad concept has been promoted for other benthic trawls (e.g. targeting pandalids; He et al., 2007).

Further support for replacing otter boards with a beam might be the associated lower drag, although the magnitude would need to be greater than that observed here. Through partitioning predicted mean drag, the fuel savings associated with the beam used were <0.5 L per 40-min deployment (or 1.0 L for a double rig), which at ~\$A 1.15 $L^{-1}$ would not offset the loss of *M. macleayi* (~\$A 3.50 $kg^{-1}$) due to removing the otter boards. However, the drag of the beam could be conceivably further reduced via simple rigging changes such as replacing the rectangular bar with a more hydrodynamic profile.

The results from this study illustrate the potential for a herding effect of otter boards on penaeids, which should be considered in future studies that seek to refine trawl spreading mechanisms to either reduce drag or habitat impacts. It is also clear that such anterior trawl modifications could potentially improve species selectivity. The possibility for more holistically resolving these three key environmental issues within a single broad category of modifications has obvious practical benefits and therefore warrants additional research.

**Acknowledgements**

This study was funded by the New South Wales (NSW) Department of Primary Industries and the Australian Fisheries Research and Development Corporation (Grant no. 2011/010). Thanks are extended to the (NSW) Professional Fishermen's Association, Steve Everson, Don Johnson, Jen Marshall, Mitch Burns, Chris Barnes, Nick Sarapuk, and especially Craig Brand and Steve Kennelly.

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**Appendix 4.** Broadhurst, M.K., Sterling, D.J. and Millar, R.B. 2013. Relative engineering and catching performances of paired penaeid-trawling systems. Fish. Res. 143: 143–152.

Fisheries Research 143 (2013) 143–152

Contents lists available at SciVerse ScienceDirect

Fisheries Research

journal homepage: www.elsevier.com/locate/fishres

# Relative engineering and catching performances of paired penaeid-trawling systems

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ARTICLE INFO

*Article history:*
Received 18 July 2012
Received in revised form 22 January 2013
Accepted 28 January 2013

*Keywords:*
Drag
Fuel consumption
Otter board
Paired trawls
Penaeids
School prawn

ABSTRACT

Two paired-trawl spreading mechanisms were compared, with a view towards progressing more environmentally benign penaeid-trawling systems. Identical twin trawls (7.35-m headline) were alternately towed in a "double rig" (four otter boards) with either 18- or 36-m bridles ("short-" and "long-" double rigs) and in a "dual rig" (36-m bridles with two otter boards and a sled). At similar speeds (~1.31 m s$^{-1}$), wing-end spread per trawl was significantly greatest in the long-double (mean ± SE: 4.50 ± 0.05 m), followed by the short-double (4.27 ± 0.05 m) and dual (3.86 ± 0.05 m) rigs. The dual rig required 24% and 20% less towing force and fuel and caught significantly fewer (by ~60%) small mulloway, *Argyrosomus japonicus* per ha of foot-rope contact than both double rigs. Other standardised catches were not significantly different among configurations, although many, including school prawns, *Metapenaeus macleayi* were lower (by 25–39%) in the dual rig – which manifested as a relatively greater quantity of fuel required per kg caught (up to ~1.5 times more). When school-prawn catches were combined across double rigs and compared against the dual rig, the latter caught significantly larger individuals, but fewer per ha of foot-rope contact (by 35%); an effect that was negated when catches were re-standardised to the contact of the foot-rope and otter boards. The results show that removing otter boards reduces benthic contact, towing force, fuel consumption and bycatch, but there are negative implications for penaeid catches that may require compensatory offsets.



## 1. Introduction

Penaeids occur globally throughout tropical and temperate near-shore areas and are very important to the commercial and artisanal fisheries of many countries (Gillett, 2008). More than 100 species are targeted using a range of passive and active gears, although most of the total catch (estimated at >1 mt per annum) is harvested using otter trawls (Kelleher, 2005).

All penaeid-trawl fisheries have specific management issues and challenges, but at a broad level the key environmental concerns of most can be encapsulated in three categories: (i) unwanted benthic impacts (Hutchings, 1990; Kaiser and de Groot, 2000) and poor (ii) fossil-fuel efficiencies (Gillett, 2008; Priour, 2009) and especially (iii) species and size selectivity (Andrew and Pepperell, 1992; Kelleher, 2005). Historical recognition of these issues has led to various attempts at their independent resolution (e.g. Valdemarsen and Suuronen, 2003). However, by far the greatest effort has focused on modifying the posterior sections of trawls to include bycatch reduction devices (BRDs) or to maintain lateral-mesh openings (e.g. square-mesh codends) to improve species and/or size selectivity, and indirectly reduce unaccounted fishing mortality and the associated negative impacts on populations of key species (Broadhurst, 2000; Broadhurst et al., 2006).

While retrospectively fitted modifications have mitigated what is perhaps the most important environmental concern associated with penaeid trawling, none are 100% effective and few, if any, concomitantly address either the poor fuel efficiencies or the potential and/or perceived habitat impacts of trawls. Also, in many penaeid-trawl fisheries, there has been reluctance to adopt modifications that have had few apparent practical benefits to industries (Tucker et al., 1997).

Perhaps a more suitable approach would first involve holistic attempts at concurrently addressing at least some aspects of all three environmental issues (especially that of most concern to fishers – poor efficiencies), and start by comparing existing categories of trawling configurations to gauge the limits of what might be possible within the current technology before complicating additions or adjustments are made (Broadhurst et al., 2007). Such a framework makes sense, not only in terms of practicality, but also

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http://dx.doi.org/10.1016/j.fishres.2013.01.019

legislation, because simply choosing an alternative conventional configuration fits more easily within existing policy than proposing completely new gear.

Various conventional configurations of penaeid trawling systems are used throughout the world (Sterling and Eayrs, 2010), but the most common involves two trawls (stretched mesh openings – SMO of 30–55 mm); typically towed independently in a 'double rig' (with two sets of otter boards) from booms on either side of a vessel (Vendeville, 1990; Gillett, 2008; Fig. 1a and b). Alternatively, two trawls can be linked together between a sled and two otter boards and towed in a 'dual rig' from a single warp over the stern (Gillett, 2008; Fig. 1b).

In terms of the three key environmental concerns listed above, dual rig has less bottom contact (habitat impact) simply because of two fewer otter boards, and conceivably should be associated with much less drag (and therefore fuel usage). The impacts on species and/or size selectivity associated with removing two otter boards are less clear, although they are known to herd teleosts (e.g. Wardle, 1986), and in a recent, preliminary study, Broadhurst et al. (2012) suggested that otter boards also contribute towards penaeid catches (but this relationship warrants further investigation). Despite the widespread global use of both dual- and double-rigged penaeid trawls, few data are available describing their relative performances.

The aim of this study was to investigate the relative engineering and catching performances of both configurations at one fishery in New South Wales (the Clarence River), Australia. This fishery involves ~93 boats, all currently towing double-rigged trawls (each with a headline length of 7.35 m) to target school prawns, *Metapenaeus macleayi*. Like many coastal penaeid fisheries around the world, the gears are used in shallow water (mostly <15 m). Owing to the water depth, Clarence River fishers typically deploy their trawls ~40 m behind the vessel, with most of the deployed cables comprising just the bridles (Fig. 1a; following convention for penaeid-trawl systems, bridles refer to the sections of wire from the end of the single warp to the doors as described by Gillett, 2008). A coherent comparison of the performances of dual and double rigs would be to attempt to maintain the same otter-board and sweep angles between systems (and therefore spread); which require the bridle length of the dual rig to be twice that of a double rig (Fig. 1a and c). We therefore compared a dual rig with 36-m bridles (standard bridle length for this fishery) against a double rig with 18-m bridles. However, to provide a relative comparison of the effectiveness of the dual rig under commercial conditions in this fishery, we also included the conventional double rig with 36-m bridles. While the study was restricted to one location, the relative performances of the two systems have broader application across all penaeid-trawl fisheries.

## 2. Methods

The experiment was done over 10 days during January and February 2012 in the Clarence River using a local trawler (10 m and 89 kw) fishing in mostly 5–10 m of water. The vessel had separate hydraulic winches amidships; each attached to 5-mm diameter (⌀) stainless warps and then bridles that were adjustable to 36- and 18-m (Fig. 1a–c). Two booms (6.75 m long from vessel centre line) were located amidships (and with blocks at their ends) for double rig, while a gantry was positioned at the stern to facilitate deployment of the dual rig (Fig. 1a–c). The trawler was equipped with: a fuel monitor (Floscan series 9000); global positioning system (GPS; Lowrance); attachable load cells and associated data logger (Amalgamated Instrument Company; model nos. PA6139 and TP4); and a portable acoustic trawl-monitoring system (Notus Trawlmaster System; model no. TM800ET). The trawl-monitoring system comprised a computer processing unit, hull-mounted omnidirectional hydrophone (located parallel to the vessel winches), and two cylindrical transducers and associated slaves (each 330-mm long × 77-mm ⌀; 1.1 kg in water); all designed to be mounted onto the trawl wing-ends (Fig. 1f).

Two identical four-seam trawls (7.35 m headline) were constructed from nominal 42-mm mesh (1.5-mm ⌀ twisted polyethylene – PE twine) and rigged with blubber-chute BRDs (nominal 92-mm mesh and 2.0-mm ⌀ twisted PE twine; see also Broadhurst and Kennelly, 1996 for a description) and square-mesh codends (nominal 27-mm mesh made from 2.25 mm ⌀ braided polyamide twine, and hung on the bar) (Figs 1f, g and 2). Each trawl was labelled (A and B) and attached to three 2.89-m sweeps on each wing; the anterior ends of which were clipped to either four 1.07-m × 0.76-m cambered-steel otter boards (54 kg each in air) and 36- or 18-m bridles for (i) 'long'- and (ii) 'short'-double rigs, or two of the same otter boards above, a sled (84 kg in air) and 36-m bridles for (iii) dual rig (Figs. 1 and 2). The sled and otter boards all had base plates that were 100 mm wide.

### 2.1. Experimental design and data collected

Prior to testing, the two trawls were weighed and 10 randomly selected meshes were measured (for SMO) in the trawl bodies, blubber chutes and codends, using a local, purpose-built gauge. Owing to the time required to change configurations, it was not possible to replicate each within a single fishing day. Rather, the three configurations were sequentially and randomly tested in blocks over 1.5 days. Specifically, at the start of each day, the two trawls were alternately clipped to either side within one of the configurations, and between two and four replicate 40-min deployments completed. The second and third configurations were then similarly fished during the afternoon and following morning, respectively. The entire sequence was repeated over a total of 10 days.

Various technical and biological data were collected during, and at the end of, each deployment. The technical data included the: (i) total fuel (to the nearest 0.1 L) consumed per 40-min deployment (period between otter boards on and off the bottom); (ii) the total distance trawled (m); (ii) towing force (kgf) on the bridles/warp attached to each configuration (recorded by two load cells for each of the double-rig configurations and one load cell for dual rig, based on a sample rate of one second, averaged over a minute); (iv) speed over the ground (m $s^{-1}$); (v) distance of the trawls from the hydrophone (m); and their (vi) wing-end spreads (m). The latter three variables were simultaneously recorded at ~60-s intervals (based on a 30-s sample rate). Engine rpm was also recorded, but remained constant at 1500 and 1700 for the dual- and double-rigs, respectively.

At the end of each deployment, catches were separated by trawl, and data collected on the total weights of school prawns and bycatch, the numbers of each bycatch species, and total lengths (TL in mm) of the most abundant teleosts. For mulloway (the most abundant teleost and caught across a range of sizes), catches were further separated and into small (<9.5 cm TL) and large (≥9.5 cm TL) individuals. Random samples of ~500 g of school prawns from each trawl were placed into plastic bags and transferred to the laboratory, where at least 100 individuals measured (carapace length – CL in mm), weighed and counted. The latter data were used to estimate the total number and mean CL caught during each deployment.

### 2.2. Analyses of spreading-mechanism configurations

Most of the data were analysed using linear mixed models (LMMs). For data that were measured for each trawl, the LMMs included 'spreading-mechanism configuration' (dual vs short-double vs long-double rigs) as fixed, while 'trawls', 'sides',

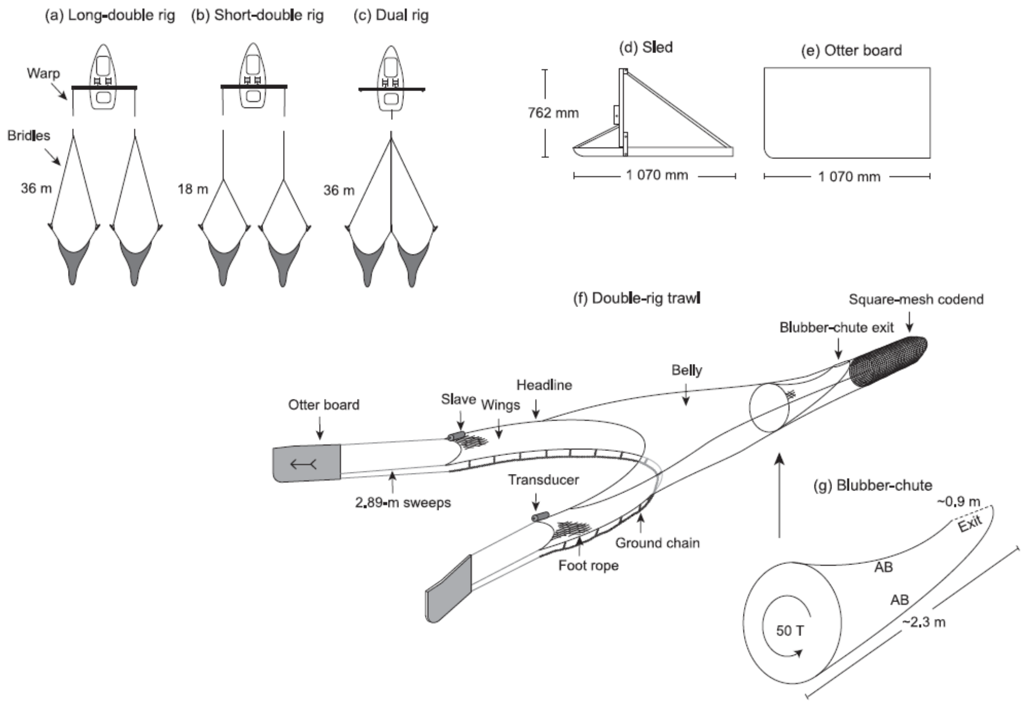


**Fig. 1.** Diagrammatic representation of (a) dual, and (b) long-double, and (c) short-double rigs, (d) dual-rig sled, (e) otter boards, (f) trawl, and (g) blubber-chute bycatch reduction device used in the experiment. AB, all bars; T, transversals.

'days' and the interactions between 'deployments' and days were included as random terms. However, for data that were measured at the deployment level (e.g. speed and fuel for all three configurations and drag for dual rig), deployment becomes the error term and so the trawl and side terms are no longer relevant. A fixed effect of speed and an additional random term of 'load cell' were included in the towing-force analyses, while speed over the ground and distance of the trawls behind the vessel were included as fixed effects in the analyses of spread and fuel usage. The significance of spreading-mechanism configuration was determined using a likelihood ratio test (LRT) and, where the overall $H_0$ was rejected, pairwise differences were subsequently explored using the Benjamini–Hochberg–Yekutieli procedure to control the false discovery rate (FDR; Benjamini and Yekutieli, 2001). Size–frequency distributions for the most abundant fish were pooled and graphed.

Relevant back-transformed predicted means from the LMMs were used to calculate relative fuel consumption associated with towing the three spreading-mechanism configurations. The fuel used per kg of school prawns caught was calculated using the absolute predicted mean prawn weights, derived by fitting the same LMM above to the unstandardised log-transformed data.

### 2.3. Analyses of the effects of otter boards on catches of school prawns

A second group of analyses was done to explore the potential for the presence of otter boards to explain some of the observed variability in catches of school prawns between dual (two otter boards) and double (four otter boards) rigs. Because school prawns are predominantly located in the substrate (Ruello, 1973; Coles, 1979) and their responses are limited to tactile stimulation, and based on the results from the models above (see Section 3), bridle length was hypothesised not to impact on their standardised catches. Therefore, to increase statistical power, data for the short- and long-double rigs were combined.

The numbers and weights of school prawns were first standardised to per ha trawled of the foot rope and along with raw mean CL and the number of school prawns per 500 g were analysed using the same LMMs as above. The numbers and weights of school prawns were then re-analysed after being standardised to the swept area of the foot rope and otter boards combined (i.e. (wing-end spread + span of otter-board contact) × the distance trawled), where the span of each otter-board contact was calculated by multiplying the otter-board length (1.07 m) by the sine of the angle of attack (based on mean wing-end spread and calculated as 31°, 33° and 36° for the dual and short- and long-double rigs, respectively). Because the relatively thin sled-base plate (100 mm) in the centre of the dual rig was outside the wing ends and in line with the direction of towing (see Section 3 and Fig. 1a), it was not included in the revised swept area. Differences in the outcomes of the LMMs for the numbers and weights of school prawns provided some indication of the effects of otter boards.

## 3. Results

Over ten days fishing, 24, 23 and 21 deployments were completed for the dual- and short- and long-double rigs, respectively, catching totals of 1624 and 349 kg of school prawns and bycatch. In terms of numbers, school prawns accounted for 96% of the total,

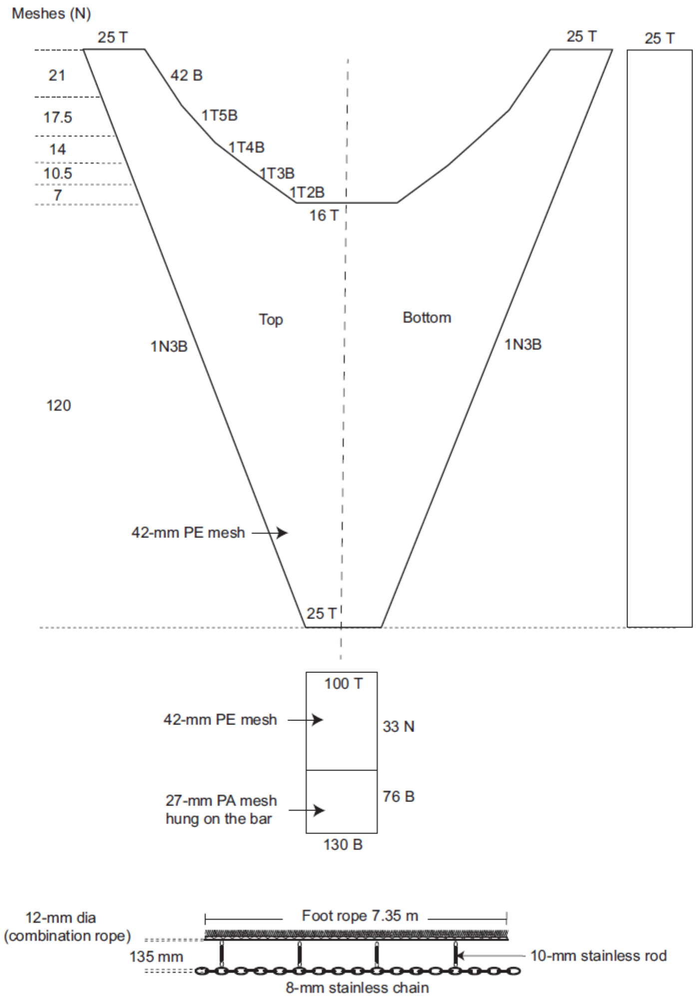


**Fig. 2.** Plan of the trawls used. T, transversals; B, bars; N, normal; PA, polyamide; PE, polyethylene; dia, diameter.

while >3% of the remaining catch comprised nine bycatch species (mostly teleosts and especially the economically important mulloway, *Argyrosomus japonicus*; Table 1). Analyses of catch data were limited to these ten species.

### 3.1. Technical variables

There were no significant differences between trawls for the SMO in their bodies (overall mean ± SE of 42.20 ± 0.17 mm), blubber-chutes (92.25 ± 0.30 mm) or codends (27.10 ± 0.10 mm) (LM, $p > 0.05$). Including sweeps, both trawls weighed 32.79 kg each, which contributed towards total system weights of 257.58 and 281.58 kg for the dual and double rigs, respectively.

Technical data were successfully collected for all deployments, except for one and three replicates of the short-double and dual rigs (on the same day), during which a load cell malfunctioned, precluding measurement of tow force. There were significant main effects of spreading-mechanism configuration on the wing-end spread per trawl, trawled area, tow force and fuel consumed (LMM, $p < 0.01$; Table 2), but not speed across the ground (overall predicted mean of $1.31 \pm 0.02\ \mathrm{m\,s^{-1}}$; LMM, $p > 0.05$; Tables 2 and 3). The LMMs found significant effects of speed on wing-end spread ($p < 0.001$), load ($p < 0.001$) and fuel ($p < 0.05$). Hence, for ease of interpretation the configuration effects stated below for spread, load and fuel are from models with speed set at the mean value of $1.31\ \mathrm{m\,s^{-1}}$. There was no significant main effect of distance behind the vessel on wing-end spread ($p > 0.05$) however an interaction between this factor and spreading mechanism returned a $p$-value of 0.06, with some evidence of a positive relationship for dual rig.

Table 1
Scientific and common names and numbers of organisms caught during the experiment.

| Family | Scientific name | Common name | n |
|---|---|---|---|
| ***Crustaceans*** | | | |
| Penaeidae | *Metapenaeus macleayi* | School prawns[a] | 696,000 |
| | *Penaeus monodon* | Tiger prawn[a] | 3 |
| Palaemonidae | *Macrobrachium novaehollandiae* | Freshwater prawn | 776 |
| Portunidae | *Scylla serrata* | Mud crab[a] | 4 |
| ***Teleosts*** | | | |
| Ambassidae | *Ambassis jacksoniensis* | Port Jackson glassfish | 757 |
| | *Ambassis marianus* | Ramsey's perchlet | 1711 |
| Anguillidae | *Anguilla australis* | Southern shortfin eel[a] | 1 |
| Apogonidae | *Siphamia roseigaster* | Pink-breasted siphonfish | 7 |
| Ariidae | *Arius graeffei* | Forktail catfish[a] | 4620 |
| Clupeidae | *Herklotsichthys castelnaui* | Southern herring[a] | 2051 |
| Dasyatididae | *Dasyatis* sp | Stingray | 27 |
| Eleotrinae | *Gobiomorphus australis* | Striped gudgeon | 13 |
| Engraulidae | *Engraulis australis* | Australian anchovy | 1 |
| Gerreidae | *Gerres subfasciatus* | Silver biddy[a] | 261 |
| Mugilidae | *Mugil cephalus* | Bully mullet[a] | 9 |
| Muraenesocidae | *Muraenesox bagio* | Common pike eel | 5 |
| Paralichthyidae | *Pseudorhombus arsius* | Largetooth flounder[a] | 103 |
| Platycephalidae | *Platycephalus fuscus* | Dusky flathead[a] | 9 |
| Plotosidae | *Euristhmus lepturus* | Longtail catfish | 1083 |
| Pomatomidae | *Pomatomus saltatrix* | Tailor[a] | 229 |
| Priacanthidae | *Priacanthus macracanthus* | Red bigeye | 14 |
| Sciaenidae | *Argyrosomus japonicus* | Mulloway[a] | 11,004 |
| Sillaginidae | *Sillago ciliata* | Sand whiting[a] | 54 |
| Soleidae | *Synclidopus macleayanus* | Narrow banded sole | 2259 |
| | *Synaptura nigra* | Black sole[a] | 22 |
| Sparidae | *Acanthopagrus australis* | Yellowfin bream[a] | 527 |
| | *Rhabdosargus sarba* | Tarwhine[a] | 9 |
| Tetraodontidae | *Tetractenos glaber* | Toadfish | 54 |
| Tetrarogidae | *Notesthes robusta* | Bullrout | 163 |

[a] Economically important.

Table 2
Summaries of likelihood ratio test (LRT) statistics from linear mixed models assessing the importance of the fixed effect of trawl configuration (dual, and short-double rings and long-double rigs) in explaining variability among technical and biological responses, and false-discovery-rate (FDR) adjusted paired comparisons of significant differences. Numbers and weights were standardised to per hectare trawled, calculated using the foot-rope contact (average wing-end spread) and then log-transformed.

| | LRT | FDR |
|---|---|---|
| **Technical variables** | | |
| Wing-end spread | 90.93*** | Dual < short-double < long-double |
| Trawled area | 21.89** | Dual < short-double = long-double |
| Tow force | 46.54** | Dual < short-double = long-double |
| Fuel consumed | 86.53*** | Dual < short-double = long-double |
| Speed across the ground | 1.35 | |
| **Biological variables** | | |
| Wt of school prawns | 3.69 | |
| No. of school prawns | 4.61 | |
| Mean CL of school prawns | 4.11 | |
| No. of school prawns 500 $g^{-1}$ | 4.17 | |
| Wt of total bycatch | 1.87 | |
| No. of total bycatch | 3.95 | |
| No. of total mulloway | 5.14 | |
| No. of mulloway ≥ 9.5 cm TL | 1.70 | |
| No. of mulloway < 9.5 cm TL | 6.80* | Not separated |
| No. of forktail catfish | 4.97 | |
| No. of narrow banded sole | 4.34 | |
| No. of southern herring | 0.19 | |
| No. of Ramsey's perchlet | 0.76 | |
| No. of longtail catfish | 1.42 | |
| No. of freshwater prawn | 0.34 | |
| No. of Port Jackson glassfish | 0.65 | |
| No. of yellowfin bream | 4.69 | |

* $p < 0.05$.
** $p < 0.01$.
*** $p < 0.001$.

False-discovery-rate paired comparisons for spreading-mechanism configuration revealed significantly and incrementally less wing-end spread per trawl between the long- (predicted mean ± SE of 4.50 ± 0.05 m) and short-double (4.27 ± 0.05 m) and dual rigs (3.86 ± 0.05 m) ($p < 0.001$). Using these predicted spreads and known vessel geometry and sweep length (2.89 m), the distances between inside wings of the paired trawls were calculated as ~1.6, 6.1, and 5.6 m for the dual, short-double and long-double rigs. For each 40-min deployment, the foot ropes in the dual rig also trawled a significantly (FDR, $p < 0.01$) smaller area (2.44 ± 0.08 ha) and the configuration required less force (475.24 ± 26.01 kgf) and fuel (8.62 ± 0.12 L) than either the short- (2.84 ± 0.08 ha, 625.14 ± 9.32 kgf, and 10.63 ± 0.12 L, respectively) or long-double (2.99 ± 0.08 ha, 624.75 ± 9.44 kgf, and 10.65 ± 0.13 L) rigs; both of which were not significantly different (FDR, $p > 0.05$; Table 3). The dual rig required less fuel than either of the double rigs in respect to ha trawled, but more when considering L per kg of school prawns (see below and Table 3).

### 3.2. Biological variables

The only biological variable significantly affected by spreading-mechanism configuration was the standardised and log-transformed numbers of small (<9.5 cm TL) mulloway (LMM, $p < 0.05$; Table 2 and Figs. 3g and 4a). Compared to the double rigs, the dual rig caught up to 61% fewer per ha of foot-rope contact (back-transformed means), although these differences were not separated by FDRs ($p > 0.05$; Table 2 and Fig. 3g).

While there were no other significant effects, compared to both double rigs, the back-transformed predicted mean catches per ha of foot-rope contact of several of the most abundant species were lower in the dual rig (LMM, $p > 0.05$; Table 2 and Fig. 3). These

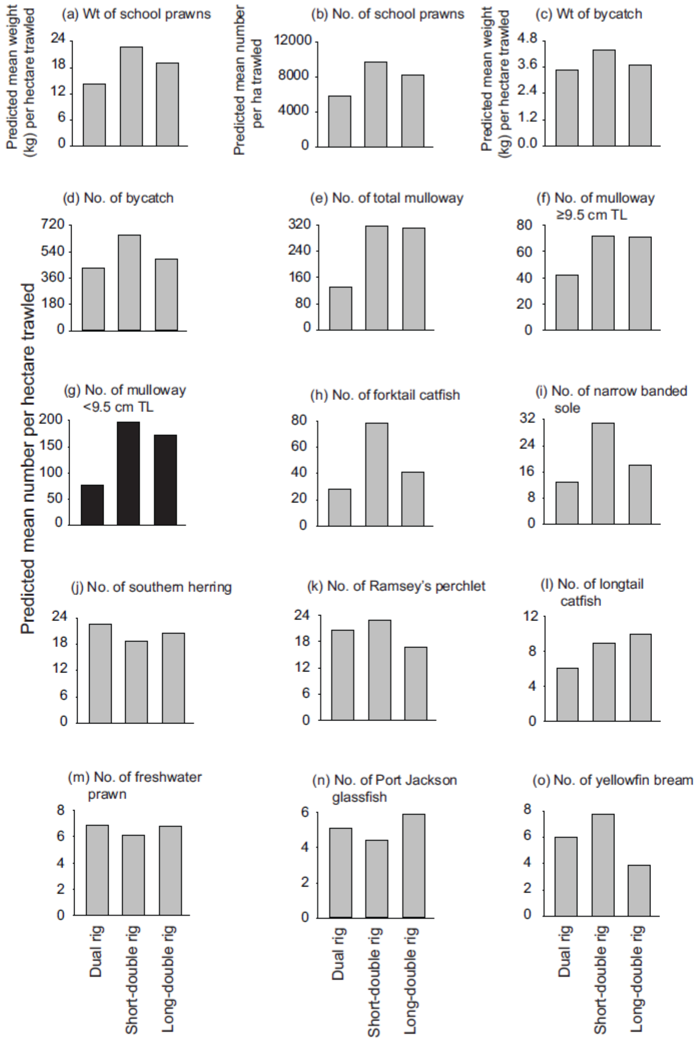


**Fig. 3.** Differences in predicted mean back-transformed catches per hectare trawled (swept area of the foot rope) between the dual and short- and long-double rigs: (a) weights and (b) numbers of school prawns, *Metapenaeus macleayi*, (c) weights and (d) numbers of bycatch, and numbers of (e) total, (f) ≥9.5 cm TL, (g) <9.0 cm TL mulloway, *Argyrosomus japonicas*, (h) fork tail catfish, *Arius graeffei*, (i) narrow banded sole, *Synclidopus macleayanus*, (j) southern herring, *Herklotsichthys castelnaui*, (k) Ramsey's perchlet, *Ambassis marianus*, (l) longtail catfish, *Euristhmus lepturus*, (m) freshwater prawn, *Macrobrachium novaehollandiae*, (n) Port Jackson glassfish, *Ambassis jacksoniensis* and (o) yellowfin bream, *Acanthopagrus australis*. Black histograms represent a significant effect of spreading-mechanism configuration detected in linear mixed models.

**Table 3**
Summary of selected mean performance and environmental impact indicators for the dual and short- and long-double rigs. Total-system contact was calculated as the sum of the mean predicted foot-rope (wing-end spread) and otter-board contacts (1.08, 2.32 and 2.49 m, respectively) within the three configurations, and the sled baseplate (100 mm) for the dual rig. FR, foot-rope contact.

| Configuration | Foot-rope contact (m) | Total-system contact (m) | Tow force (kgf) | Fuel rate ($L\,h^{-1}$) | Fuel consumption | |
|---|---|---|---|---|---|---|
| | | | | | $L\,ha^{-1}$ (FR) | $L\,kg^{-1}$ (prawn) |
| Dual | 7.72 | 8.80 | 475.24 | 12.93 | 3.53 | 0.52 |
| Short-double | 8.54 | 10.86 | 625.14 | 15.94 | 3.74 | 0.34 |
| Long-double | 9.00 | 11.90 | 624.75 | 15.97 | 3.56 | 0.38 |

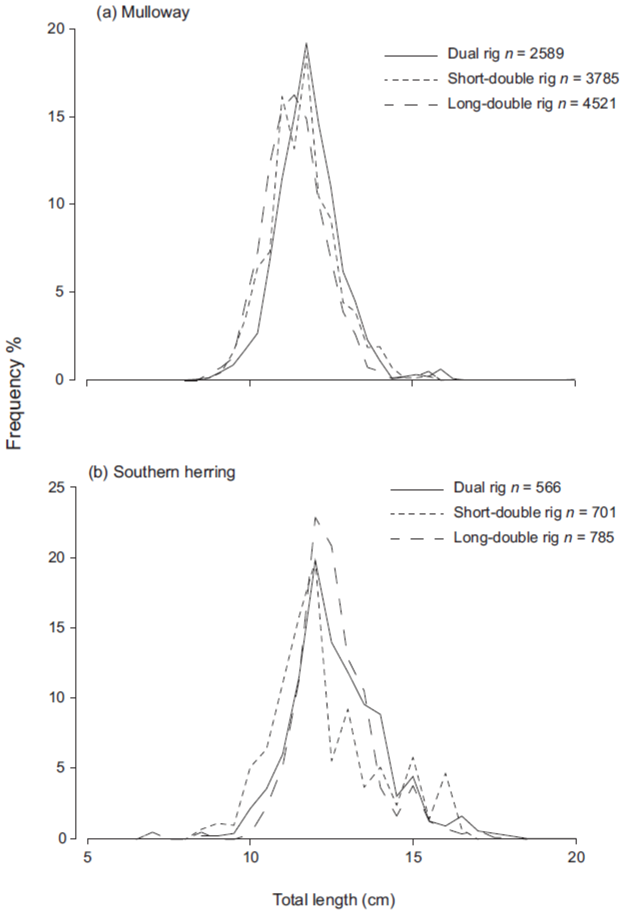


**Fig. 4.** Size–frequency distributions between the dual and short- and long-double rigs for (a) mulloway, *Argyrosomus japonicas* and (b) southern herring, *Herklotsichthys castelnaui*.

variables included the numbers and weights of school prawns (by 25–39%) and total bycatch (by 5–34%), and the numbers of total mulloway (58 and 57%) and those ≥9.5 cm TL (40 and 39%), forktail catfish, *Arius graeffei* (64 and 32%), narrow banded sole, *Synclidopus macleayanus* (58 and 28%) and longtail catfish, *Euristhmus lepturus* (33 and 39%) (Fig. 3a–f, h, i and l). Further, the *p*-values for total mulloway and forktail catfish were close to 0.08 (Table 2). Catches of other, mostly less abundant, species showed few differences (Figs. 3 and 4b). Although not significant, on average the dual rig retained slightly larger school prawns (predicted mean CL and number per 500 g of 14.32 ± 0.10 mm and 207.62 ± 4.44) than the short-double (14.15 ± 0.10 mm and 214.77 ± 4.46) or long-double (14.13 ± 0.11 mm and 216.11 ± 4.63) rigs (Fig. 5).

### 3.3. Effects of otter boards on catches of school prawns

Compared to the combined-double rigs (and similar to the above), the dual rig retained significantly larger school prawns (14.32 ± 0.10 mm CL and 207.67 ± 4.44 per 500 g vs 14.14 ± 0.09 mm CL and 215.39 ± 3.97 per 500 g), but fewer per ha of foot-rope contact, with a predicted mean that was 35% lower (LMM, $p < 0.05$; Table 4 and Fig. 6a). The latter significant difference was not maintained when catches were standardised to per ha of the combined foot-rope and otter boards contact (although the predicted mean was still 27% less); indicating that the absence of otter boards explained at least some of the reductions in numbers of school prawns by the dual rig (LMM, $p > 0.05$; Table 4 and Fig. 6a). The weight of school prawns was not similarly significantly affected, but nevertheless followed the same trend as above (predicted mean reductions of 32% and 24% for foot-rope and combined foot-rope and otter-boards contacts; Fig. 6b).

## 4. Discussion

There were clear differences in trawl performance attributable to the spreading mechanism, and also to bridle length within double rig. Of these two broad changes, the effects of the former and more specifically the removal of two otter boards were most

**Table 4**
Summaries of likelihood ratio test (LRT) statistics from linear mixed models comparing the effects of dual- and double-rigs (combined) in explaining variability among catches of school prawns, *Metapenaeus macleayi* and, where applicable, the direction of differences. The numbers and weights were standardised to per hectare trawled, calculated using both the contact of the (i) foot-rope (average wing-end spread × distance trawled) and (ii) the foot-rope and otter boards combined (average wing-end spread + total otter board contact × distance trawled), before being log-transformed. D, dual rig; BD, both double rigs combined; –, not applicable.

| Variable | LRT | |
|---|---|---|
| | Foot-rope contact | Foot-rope and otter-board contact |
| Wt of school prawns per ha trawled | 3.21 | 1.65 |
| No. of school prawns per ha trawled | 4.20* (D < BD) | 2.38 |
| Mean CL of school prawns | 4.08* (D > BD) | – |
| No. of school prawns per 500 g | 4.08* (D < BD) | – |

* $p < 0.05$.

evident, translating to significant (i) reductions in tow force, fuel consumed and (ii) changes to size and species selectivity. The extent of these impacts can be discussed with respect to the engineering dynamics of the configurations and the known and likely behaviours of the target and key bycatch species, and then used to suggest future research into more environmentally benign penaeid-trawling systems.

The positive effect of bridle length on wing-end spread was simply attributed to the concomitant reduction in the angle at the apex of the bridle, which created less in-pull force on the otter boards for any given speed. Although the subsequent spread ratio (distance between wing ends/headline length) of the trawls in the long-double rig was low (~0.61), it was still within the range expected for such configurations (Sterling, 2000). Conceivably, longer bridles might further improve wing-end spread of the assessed trawls, although the conventional bridle length of ~36 m is dictated by the depth of water (typically <10 m) and the ratio to the length of warp deployed (typically >3:1).

It is less clear why, despite the same bridle angles, the dual rig did not produce consistently similar wing-end spreads as the short-double rig (Sterling, 2000). Previous studies have established that beyond bridle length (but within the same otter board size/area), several other technical and environmental factors significantly affect wing-end spread, including the towing speed, current, catch weight, sea conditions, bottom type, warp length and depth (e.g. Wathne, 1977; Godø and Engås, 1989; Fujimori et al., 2005; von Szalay and Somerton, 2005; Weinberg and Kotwicki, 2008). While none of these factors were confounded among the configurations tested here, the possibility exists for spreading-mechanism-specific impacts. In particular, unlike the short-double rig which was deployed with all of the 18-m bridles and an additional 18-m of warp, the dual-rig was mostly fished to the length of the 36-m bridles only, with the single warp occasionally extending into the water during slightly deeper deployments. Additional data are required to determine if the length of warp deployed has a greater effect on the wing-end spreads of this configuration than the double rigs.

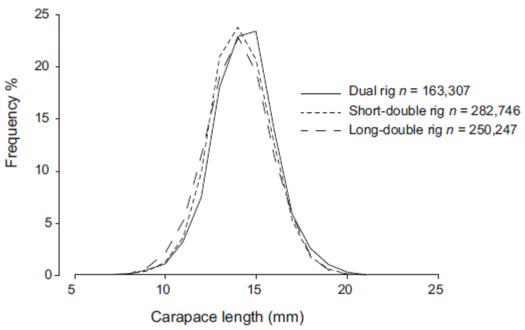


**Fig. 5.** Size–frequency distributions between the dual and short- and long-double rigs for school prawns, *Metapenaeus macleayi*.

Irrespective of the cause, the relatively lower spreads of the dual-rigged trawls do not account for the significantly lower associated tow force and improved fuel efficiency. These parameter changes can be directly attributed to the removal of the two otter boards from the system. Previous studies have suggested that the drag of otter boards can comprise up to 40% of the total for penaeid trawls (Sterling, 2000; Sterling and Eayrs, 2010). Obtaining an accurate estimate of the contribution of the otter boards to total drag here is difficult, but their removal facilitated a reduction in vessel output from 1700 to 1500 rpm to maintain approximately the same speed, and concomitantly less fuel and tow force. Therefore, the 24% reduction in average tow force for the dual rig approximates the reduction in drag due to the removal of the one pair of otter boards. The marginally lower decrease in fuel consumption (20%) may simply reflect a relatively poorer propulsive efficiency at the lower rpm.

While the energy reduction associated with fewer otter boards in the dual rig is positive, this was offset by concomitant reductions in the standardised catches of school prawns, which would preclude the commercial use of the assessed dual-rig configuration in the Clarence River (see also Broadhurst et al., 2012). Prior to discussing the possible relationship between otter boards and catches of school prawns, it is necessary to first consider the potential for any confounding influence of wing-end spread on the observed variations in catches per ha trawled. Although significant, the absolute differences in mean wing-end spread were only ~40–65 cm between the dual and both double rigs, which would translate to minimal differences in trawl geometry, and in any case were within acceptable spread ratios for these trawl designs. Further, while several other studies have shown that much larger variations among wing-end spread have significantly affected the catching efficiency of trawls for benthic organisms, this relationship typically is negative (i.e. a reduction in standardised catches with greater spread ratios) and often attributed to lower headline heights and/or less foot-rope bottom contact (e.g. Godø and Engås, 1989; Rose and Nunnallee, 1998; von Szalay and Somerton, 2005). Given the above, the significant reduction in numbers of school prawns (biased towards those that were smaller) by the dual rig was probably attributable to the absence of the otter boards; a conclusion that also supports earlier research on the effects of otter boards on catches in local penaeid trawls (Broadhurst et al., 2012).

The potential importance of otter boards on catches of school prawns can be explained by their distribution in the substratum (Ruello, 1973; Coles, 1979) and differences in the total benthic contact of the two systems—in terms of their swept areas and riverbed penetration (see also Broadhurst et al., 2012). Specifically, for the double rigs, the otter boards comprised ~22% of the total system contact (i.e. lateral spread and swept area) vs ~13% for the dual

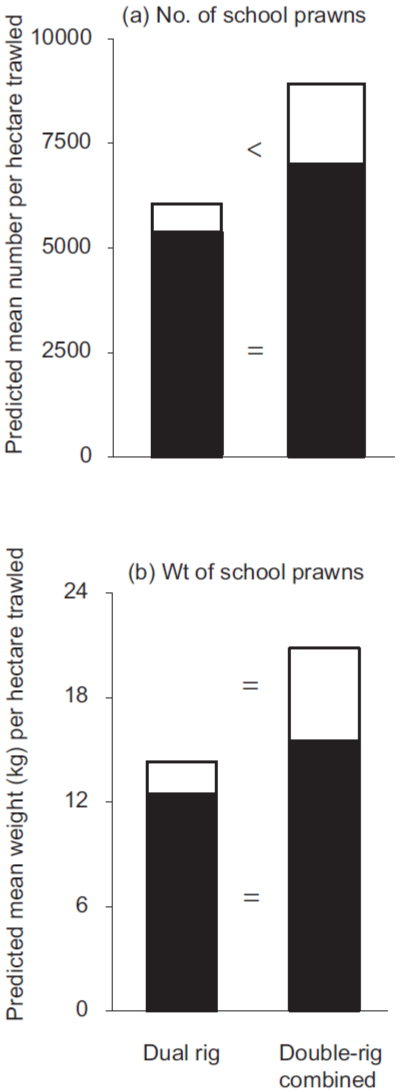


**Fig. 6.** Differences in predicted mean back-transformed catches per hectare trawled calculated using the swept area of the foot rope (entire histograms) and the foot rope and otter boards combined (black histograms) between the dual and double rigs (combined) for (a) numbers and (b) weights of school prawns, *Metapenaeus macleayi*. < and = indicate the direction of differences detected in linear mixed models.

rig. This difference does not equate to the observed reductions in predicted mean school prawn catches by the latter configuration, but the otter boards are the heaviest system component (i.e. >75% for the double rigs) and therefore potentially penetrate much deeper into the substratum than the footrope, effectively disturbing more buried school prawns which might have then been directed towards the mouth of the trawl (discussed by Broadhurst et al., 2012).

The potential for such physical impacts is further supported by the bias towards a significantly smaller mean size of school prawns in the double rig. In particular, while few data are available on the burrowing behaviour of this species (but see Ruello, 1973), studies on other penaeids have suggested a positive relationship between prawn size and their depth in substratum (e.g. Fuss, 1964; Kenyon et al., 1995). It is possible that smaller school prawns were closer to the surface of the substratum in the Clarence River, and so more were herded by the otter boards into the double-rigged trawls (Broadhurst et al., 2012).

In addition to affecting the catch rates and sizes of school prawns, the dual rig also caught relatively fewer fish, and especially small mulloway than either of the double rigs. This result might seem counter intuitive, since the quantity of a particular fish species herded into a trawl mouth typically is positively associated with their size (and therefore swimming speed; Beamish, 1978) and negatively associated with the sweep angle (Rose and Nunnallee, 1998; von Szalay and Somerton, 2005). Therefore, smaller sweep angles in the dual rig (as a consequence of less wing-end spread) might be expected to more effectively herd more smaller individuals of a species into the trawl, than the slightly larger angles in the double rigs. However, the opposite occurred for mulloway, possibly because the otter boards affected their capture more than the relatively short sweeps.

For example, those mulloway in the path of the double rigs might have detected the otter boards (or their posterior sediment clouds) and orientated away, sufficiently in advance of the sweeps to be herded into the trawl (e.g. Wardle, 1986). The same mechanisms probably occurred at the outside wings of the dual rig, but the narrow sled profile at the inside wing-end sweeps may have precluded detection by mulloway, until they were close to the sweeps. Smaller fish might not have been able to respond quickly enough to the stimulus and so passed between the inside trawl wing ends (~1.6 m apart). Any response of fish to the otter boards and sweeps would be affected by available light and water clarity (Wardle, 1986), which might explain some of the substantial variability observed in the level of differences between spreading mechanisms.

The relative engineering and catching performances of the dual and double rigs assessed here provide some direction for developing more environmentally benign penaeid-trawl spreading systems; not only for the Clarence River, but also other fisheries using similar configurations. For paired trawls, it would seem that there is a balance between minimising drag, fuel consumption, habitat contact and bycatch, while maintaining target catches. As one example, within a dual rig, drag could be maintained, but standardised catches of penaeids might be increased by using otter boards with a longer base (but the same area). The relative bottom contact of such designs would still be less than that of a double rig and so such a configuration could be an option in a particular fishery where both fuel consumption and potential habitat impacts were of concern. Alternatively, because the foot rope has a lighter bottom contact that the otter boards, wider trawls could be used in a dual rig to offset any inherent reduction in system catchability, which would minimise habitat impacts, but not necessarily drag and fuel.

Clearly, therefore, while the results indicate the potential for broad technical modifications to concurrently address the key environmental issues associated with penaeid trawls, it is also apparent that the latter form intricate, interactive relationships, and so within any given fishery there needs to be clear prioritisation of the main concerns. Notwithstanding such complexity, it would seem that otter boards are among the most important system components, and future research warrants more detailed assessment of their impacts on the efficiency of penaeid trawls across broader temporal and spatial conditions.

## Acknowledgements

This study was funded by the New South Wales (NSW) Department of Primary Industries and the Australian Fisheries Research and Development Corporation (Grant No. 2011/010). Thanks are extended to the (NSW) Professional Fishermen's Association, Steve Everson, Don Johnson, Jen Marshall, Mitch Burns, Chris Barnes, Nick Sarapuk, and especially Craig Brand.

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**Appendix 5.** Broadhurst, M.K., Sterling, D.J. and Millar, R.B. 2013. Progressing more environmentally benign penaeid-trawling systems by comparing Australian single- and multi-configurations. Fish. Res. 146: 7–17.

Fisheries Research 146 (2013) 7–17

Contents lists available at SciVerse ScienceDirect

Fisheries Research

journal homepage: www.elsevier.com/locate/fishres

# Progressing more environmentally benign penaeid-trawling systems by comparing Australian single- and multi-net configurations

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ARTICLE INFO

*Article history:*
Received 15 November 2012
Received in revised form 20 March 2013
Accepted 1 April 2013

*Keywords:*
Bycatch reduction
Drag
Fuel reduction
Otter trawling
Penaeids

ABSTRACT

The engineering and catching efficiencies of single-, double-, triple- and quad-rigged penaeid trawls (all with the same cumulative headline – 14.63 m and sweep lengths – 9.76 m) were compared across the same spatio-temporal scales in an attempt to identify the more environmentally benign configurations (in terms of species selectivity, fuel intensity and habitat contact). The relative system efficiencies reflected a complex array of interacting factors, but broadly environmental performance improved with an increasing number of nets in the configuration. The single rig had the least fishing capability due to having the lowest wing-end spread (a 'spread ratio' – SR to headline length of 63.50%), but the greatest drag, and required the most fuel (predicted mean of 2.88 L per ha trawled). Further, this system caught significantly more yellowfin bream, *Acanthopagrus australis* and fewer (but larger) of the targeted school prawns, *Metapenaeus macleayi* than the multi-trawl rigs. Compared to single rig, the double rig had an improved SR (68.76%) and was easier to tow (2.44 L per ha trawled). However, triple and quad rigs similarly achieved the greatest SRs (75.46 and 74.37%) and at lower drag and fuel consumptions (2.13 and 2.21 L per ha trawled, respectively). Providing effort is regulated, the latter two configurations, but especially triple rig (which had relatively less total benthic contact), could be the most suitable base from which to progress modifications to further reduce the environmental impacts of penaeid trawling.


## 1. Introduction

Penaeids are important to commercial fisheries throughout Australia, with 13 key species targeted; some with seines and stow and trap nets (e.g. Broadhurst et al., 2004; Macbeth et al., 2005), although the greatest effort involves trawling (ABARES, 2011). At present, the Australian penaeid-trawl industry comprises some 1300 vessels (~8–25 m) mostly towing double-, but also single-, triple- and quad-rigged otter trawls (Fig. 1; see Vendeville, 1990; Gillett, 2008 for more details) in 13 separately managed regions, with total annual landings of approximately 20,000 mt valued at A$ 250 million (ABARES, 2011).

Although Australian penaeid-trawl fisheries are quite diverse in terms of the targeted species and legislated gear configurations (including minimum and maximum mesh sizes and headline lengths), like in many overseas fisheries, they all have two common environmental issues, including poor (i) species and size selectivity (Kelleher, 2005) and (ii) high energy intensities (Gillett, 2008). Further, in some fisheries there are additional concerns regarding (iii) perceived habitat impacts (Hutchings, 1990).

Various attempts have been made to resolve these three broad issues, but the most effort by far has involved developing so-called 'bycatch reduction devices' (BRDs) and more consistent lateral-mesh openings in codends to improve species and size selectivity, and so reduce unaccounted fishing mortality (e.g. Broadhurst, 2000; Broadhurst et al., 2006). Ancillary legislated changes have included spatial (e.g. marine parks) or temporal closures in sensitive areas to further mitigate bycatch and also habitat impacts (e.g. Burridge et al., 2003). More recently, and in accord with a global trend (e.g. Parente et al., 2008; Priour, 2009), there has been a growing focus on assessing modifications to anterior sections (e.g. trawl bodies and otter boards) to improve fuel efficiencies (Sterling and Eayrs, 2010; Broadhurst et al., 2012a,b, 2013).

Most national and international attempts at resolving the above key environmental concerns associated with penaeid trawling have been done reactively and in isolation (but see Broadhurst et al., 2012a, 2013). A more suitable approach could encompass holistic strategies that attempt to concomitantly address at least some aspects of all concerns (Broadhurst et al., 2013). A starting point for

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0165-7836/$ – see front matter © 2013 Published by Elsevier B.V.
http://dx.doi.org/10.1016/j.fishres.2013.04.001

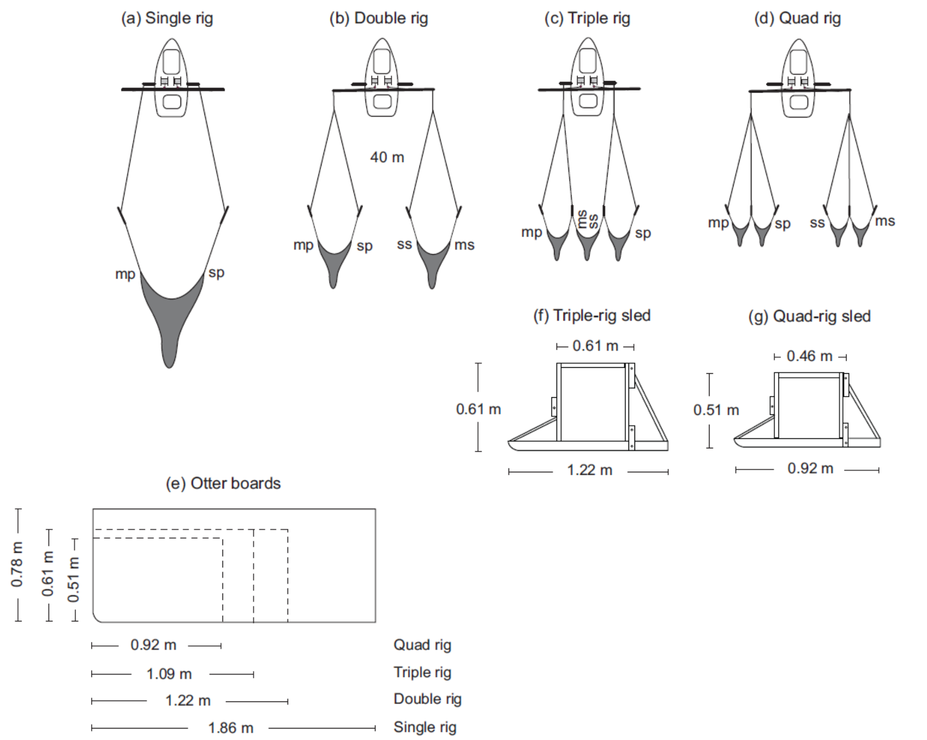


**Fig. 1.** Diagrammatic representation of (a) single-, (b) double-, (c) triple- and (d) quad-rigs, and (e) otter boards and (f) triple- and (g) quad-rig sleds. The Notus transducers and slaves were ms, master starboard; ss, slave starboard; mp, master port; and sp, slave port.

such an approach might be to assess which of the existing conventional trawling configurations have the most potential for limiting the main concerns, before attempting retrospectively fitted modifications. As one example, single- and triple-rigs have two fewer otter boards than double- and quad-rigs, and therefore at least some less bottom contact (i.e. potentially relatively fewer habitat impacts). Alternatively, increasing the number of trawls should improve swept area and with less drag, and therefore improve efficiencies (Sterling and Eayrs, 2010). Further, there is also evidence to suggest that the general spreading mechanism of penaeid trawls significantly affects their size and species selectivity (Broadhurst et al., 2012a, 2013).

Despite the above, there have been very few quantitative studies on the relative engineering and/or biological performances of common penaeid-trawl configurations (but see Andrew et al., 1991; Broadhurst et al., 2013) or for other otter trawls in general (but see Sangster and Breen, 1998). This lack of data justifies the aims of the present study, which were to: (i) compare the engineering and catching performances of single-, double-, triple- and quad-rigged generic trawls with the same cumulative headline length (14.63 m) and optimised for the same trawler; and then (ii) use this information to suggest an appropriate configuration for future research into more environmentally benign trawling systems.

The difficulty in comparing any fishing gears is the control of confounding variables, so that the key fixed factors of interest can be meaningfully interpreted (Sangster and Breen, 1998). However, because single- and multi-trawl configurations all have their own unique characteristics, it is not viable to standardise the multitude of factors implicated or known to affect otter-trawl performance. These variables include, but are not limited to, wing/body side taper and length (e.g. Conolly, 1992; Broadhurst et al., 2012b), headline height (e.g. Rose and Nunnallee, 1998), otter-board area and profile (e.g. Broadhurst et al., 2012a, 2013), and/or foot-rope geometry (e.g. von Szalay and Somerton, 2005). Rather, we have attempted to standardise the trawls as much as possible in terms of mesh size and lateral openings, cumulative sweep lengths, ground gear (and therefore bottom contact), posterior body circumferences, BRDs and codends. The various trawl configurations can be considered standardised for a particular vessel (10 m and 89 kw), representative of gear used throughout Australia, and comparable to many used in several overseas fisheries.

## 2. Methods

The experiment was done between March and May 2012 in the Clarence River using a local trawler (10 m and 89 kw) fishing in ~3–18 m of water. The vessel had two independent hydraulic winches located amidships, each fitted with a main wire (8-mm diameter Ø stainless steel) attached to three 40-m (6-mm Ø stainless steel wire) bridles. The three bridles could be passed through either of two 15-cm blocks located on lateral towing arms at 2.99 and 5.79 m from the vessel centre line (Fig. 1a and b). The trawler was also equipped with: a fuel monitor (Floscan series 9000); global positioning system (GPS; Lowrance); hull-mounted sum log (EchoPilot, Bronze Log+), attachable load cells and associated data logger (Amalgamated Instrument Company; model

**Table 1**
Technical specifications of the trawls and rigging. Twine and sled areas were calculated for those surfaces that were at an angle to the direction of towing (i.e. do not include the parallel panels of netting in the codend or extension). Total system area is the sum of the twine, ground-chain (0.146 m² for each system), otter-board, sleds, sweeps (0.176 m²) and catch areas (calculated from the maximum surface area of the square-mesh codend).

| | Single | Double | Triple | Quad |
|---|---|---|---|---|
| Trawl bodies | | | | |
| Number | 1 | 2 | 3 | 4 |
| Individual headline length (m) | 14.63 | 7.32 | 4.88 | 3.66 |
| Individual foot-rope length (m) | 16.43 | 8.70 | 6.09 | 4.83 |
| Wing end (T) | 91 | 71 | 66 | 57 |
| Lead-a-head (N) | 24 | 18 | 15 | 15 |
| Headline tapers | 126 AB; 15× (1T6B; 1T4B; and 1T2B); and 24 T | 62 AB; 6× (1T5B; 1T4B; 1T3B; and 1T2B); and 24 T | 24 AB; 7× (1T4B; 1T3B; and 1T2B); and 30 T | 31 AB; 4× (1T4B; 1T3B; and 1T2B); and 24 T |
| Body/wing side tapers | 1N6B | 1N5B | 1N4B | 1N2B |
| Individual length (m) | 12.64 | 6.64 | 5.04 | 5.67[a] |
| Individual weight (kg) | 49.60 | 21.80 | 16.60 | 14.10 |
| Total twine area (m²) | 8.87 | 6.62 | 7.07 | 7.20 |
| Otter boards | | | | |
| Number | 2 | 4 | 2 | 4 |
| Dimensions (m) | 1.86 × 0.78 | 1.22 × 0.61 | 1.09 × 0.61 | 0.92 × 0.51 |
| Individual weight (kg) | 94.00 | 45.00 | 41.00 | 30.00 |
| Baseplate width (mm) | 75 | 75 | 75 | 75 |
| Total area (m²) | 2.90 | 2.98 | 1.33 | 1.88 |
| Sleds | | | | |
| Number | 0 | 0 | 2 | 2 |
| Dimensions (m) | Na | Na | 1.22 × 0.61 | 0.92 × 0.51 |
| Individual weight (kg) | Na | Na | 55.00 | 38.00 |
| Baseplate width (mm) | 100 | 100 | 100 | 100 |
| Total area (m²) | Na | Na | 0.015 | 0.013 |
| Sweeps | | | | |
| Individual length (m) | 4.88 | 2.44 | 1.63 | 1.22 |
| Total weight (kg) | 3.86 | 3.86 | 3.86 | 3.86 |
| Codend/extension | | | | |
| Length (m) | 2.40 | 2.40 | 2.40 | 2.40 |
| Individual weight (kg) | 5.80 | 5.80 | 5.80 | 5.80 |
| Total catch area (m²) | 0.23 | 0.46 | 0.69 | 0.92 |
| Total trawl/codend length (m) | 15.04 | 9.04 | 7.44 | 8.07 |
| Total system weight (kg) | 247.92 | 239.06 | 262.96 | 279.36 |
| Total system area (m²) | 12.67 | 10.73 | 9.78 | 10.68 |

T, transversals; N, normal; B, bars; Na, not applicable.
[a] Includes 30 N (1.26 m) of an additional extension attached to the trawl body to facilitate codend retrieval.

nos. PA6139 and TP4); and a portable acoustic, trawl-monitoring system (Notus Trawlmaster System; Model no. TM800ET). The trawl-monitoring system comprised a computer processing unit, hull-mounted omnidirectional hydrophone (located adjacent to the vessel winches), and two cylindrical transducers and associated slaves (each 330-mm long × 77-mm Ø; 1.1 kg in water); all designed to be mounted onto the trawl wing-ends.

### 2.1. Trawl configurations

Ten four-seam trawls were constructed from nominal 42-mm (stretched mesh opening – SMO) mesh (1-mm Ø twisted polyethylene twine), all with the same knot directions (Table 1; Fig. 2). All trawls had the same cumulative sweep length (9.76 m total) and ground-gear configurations (comprising 77 and 23% of 8- and 10-mm stainless-steel chain, with 6-mm stainless-steel chain drops covered by 35-mm Ø plastic tube; Fig. 2), and similar clusters of headline and foot-rope tapers, appropriate lead-ahead, and posterior trawl-body circumferences (~150 T) (Table 1).

However, there were different headline lengths according to configuration: single- (1× 14.63 m); double- (2× 7.32 m); triple- (3× 4.88 m); and quad-rig (4× 3.66 m) (Table 1). The trawls also had configuration-specific body tapers and otter boards (and therefore wing heights – dictated by otter-board heights) (Table 1; Figs. 1e and 2). These subtle variations in trawl specifications ensured that despite the differences in overall size, the trawls had similar fractional lateral mesh openings during fishing. The quad-rigged trawls also had an additional extension of 30 N × 150 T of trawl mesh attached at the posterior body to increase the length to facilitate codend retrieval (Table 1).

Zippers (Buraschi S146R, 1.45 m long) were attached to each of the posterior trawl bodies, and to four extension sections (with 28-mm bar-spaced Nordmøre-grids installed) and codends (made from 1.25-mm Ø twine, 27-mm mesh hung on the bar) (Table 1; Fig. 2). The extension/codends were labelled and always allocated to the same trawl within configurations.

All trawl configurations (and their rigging) were weighed and 20-randomly selected meshes in the bodies/wings, extensions and codends were measured for stretched mesh opening (SMO), using a local purpose-built gauge. The total surface areas of the four systems subjected to drag were calculated by summing the areas of the (i) meshes that were at an angle to the direction of towing (i.e. excluding parallel sections in the codends and extensions), (ii) catch (calculated assuming a constant diameter in the square-mesh codends), (iii) anterior otter-board and sled profiles, and (iv) all other standardised parameters (e.g. sweeps, ground gear and fishing lines) (Table 1).

### 2.2. Spreading-mechanism configurations

Twelve flat, rectangular otter boards (steel frames and timber sheeting) were constructed, including: (i) two 1.86 m × 0.78 m (94 kg each) for the single rig; (ii) four 1.22 m × 0.61 m (45 kg each) for the double rig; (iii) two 1.09 m × 0.61 m (41 kg each) for the triple rig; and (iv) four 0.92 m × 0.51 m (30 kg each) for the quad rig (Table 1; Fig. 1e). Two sets of steel sleds were built for the

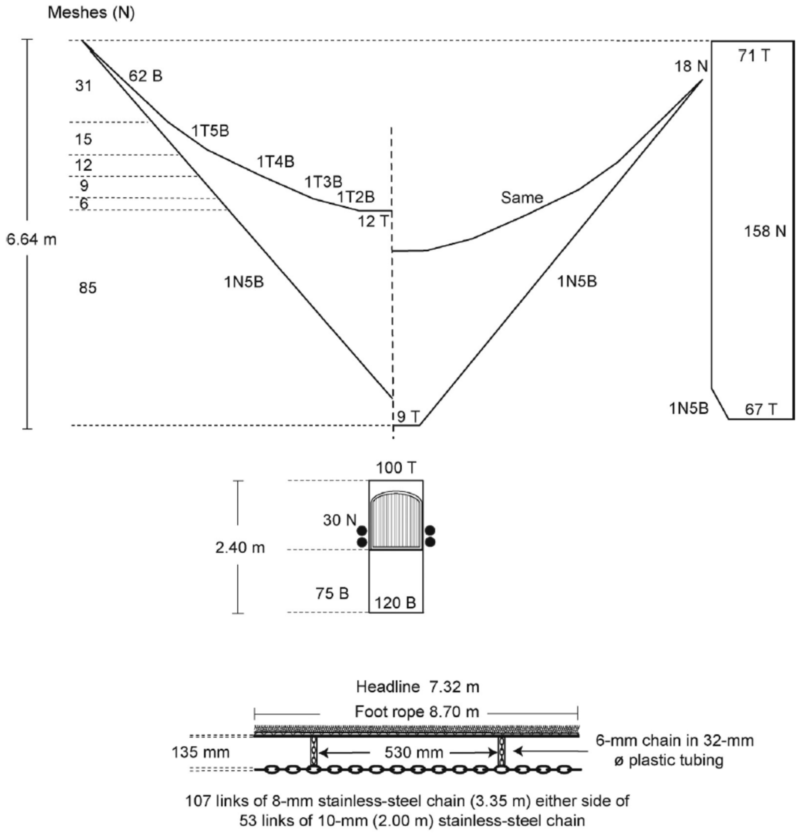


**Fig. 2.** Plan of the double-rig trawl body, codend and extension section with Nordmøre-grid. All other trawls followed a similar design, as described in Table 1.

triple- (1.22 m × 0.61 m and 55 kg) and quad-rigs (0.92 m × 0.51 m and 38 kg) (Fig. 1f and g). The dimensions of the various spreading-mechanism components were chosen based on typical existing penaeid trawling-systems used throughout Australia, and to maximise performance in terms of optimal wing-end spreads with respect to minimum drag. Designing each configuration for maximum performance produced specifications well within the range of conventional gear (Sterling, 2005).

### 2.3. Experimental design and statistical analyses

Owing to the time required to change trawl configurations, it was not possible to replicate all within a single fishing day. Instead, the systems were sequentially and randomly tested in four-day 'blocks' during each of six weeks. Specifically, at the start of the first day, one of the trawl configurations was randomly selected and rigged to the vessel. A Notus transducer and slave were attached to each wing-end of the trawls in the (i) single- and (ii) double-rigs, (iii) two pairs on each side of the vessel in the quad rig, and (iv) centre and outside pairs in the triple rig (Fig. 1a–d). Three replicate 35-min deployments were then completed, before a second trawl configuration was rigged to the vessel and similarly fished during the afternoon. The third and fourth configurations were fished on the following day. The entire sequence was then repeated (randomised within blocks) over an additional two days in each week. All deployments were done across the same fishing ground, with the vessel maintaining a consistent heading, except for a single 180° turn, to ensure equal sampling against and with the current.

Various data were collected during, and at the end of, each deployment. Technical data included the: (i) total fuel (to the nearest 0.1 L) consumed per 35-min deployment (period between otter boards on and off the bottom); (ii) the total distance trawled (m); (iii) drag (kgf) on each of the warps attached to each system (recorded at 60-s intervals by two load cells and summed to provide the total drag), speed (m $s^{-1}$); (iv) over the ground (SOG), and (v) through the water (STW); (vi) depth fished (m); (vii) distance of the trawls from the hydrophone (m); and the (viii) wing-end spreads (m). The latter six variables were simultaneously recorded at ~60 s intervals.

The wing-end spreads for the individual trawls in the triple- and quad-rigs were calculated after adjusting for the span of the sleds and sweeps (Table 1; Fig. 1c and d). For the triple rig, the wing-end spread of the centre net was disguisable from the entire system, while for quad rig, differential wing-end spread was limited to each pair of trawls on each side of the vessel. Predicted wing-end spreads (below) were used to calculate otter-board angles of attack (from the model proposed by Sterling, 2005) and subsequent benthic contact (by multiplying otter-board length by the sine of

**Table 2**
Scientific and common names and numbers of organisms caught during the experiment.

| Family | Scientific name | Common name | Numbers |
|---|---|---|---|
| Crustaceans | | | |
| Penaeidae | *Metapenaeus macleayi* | School prawn[a] | 394,935 |
| | *Penaeus monodon* | Tiger prawn[a] | 1 |
| Palaemonidae | *Macrobrachium novaehollandiae* | Freshwater prawn | 263 |
| Teleosts | | | |
| Ambassidae | *Ambassis jacksoniensis* | Port Jackson glassfish | 18 |
| | *Ambassis marianus* | Ramsey's perchlet | 171 |
| Anguillidae | *Anguilla australis* | Southern shortfin eel[a] | 15 |
| Ariidae | *Arius graeffei* | Forktail catfish[a] | 10,334 |
| Clupeidae | *Herklotsichthys castelnaui* | Southern herring[a] | 132 |
| Eleotrinae | *Gobiomorphus australis* | Striped gudgeon | 1 |
| Engraulidae | *Engraulis australis* | Australian anchovy | 1 |
| Gerreidae | *Gerres subfasciatus* | Silver biddy[a] | 487 |
| Hemiramphidae | *Arrhamphus sclerolepis* | Snubnose garfish[a] | 2 |
| Mugilidae | *Mugil cephalus* | Bully mullet[a] | 1 |
| Muraenesocidae | *Muraenesox bagio* | Common pike eel | 1 |
| Monodactylidae | *Monodactylus argenteus* | Diamond fish | 7 |
| Percichthyidae | *Macquaria novemaculeata* | Australian bass[a] | 1 |
| Platycephalidae | *Platycephalus fuscus* | Dusky flathead[a] | 31 |
| Plotosidae | *Euristhmus lepturus* | Longtail catfish | 8 |
| Pomatomidae | *Pomatomus saltatrix* | Tailor[a] | 8 |
| Sciaenidae | *Argyrosomus japonicus* | Mulloway[a] | 300 |
| Sillaginidae | *Sillago ciliata* | Sand whiting[a] | 2 |
| Soleidae | *Synclidopus macleayanus* | Narrow banded sole | 642 |
| Sparidae | *Acanthopagrus australis* | Yellowfin bream[a] | 1015 |
| | *Rhabdosargus sarba* | Tarwhine[a] | 1 |
| Terapontidae | *Pelates quadrilineatus* | Trumpeter[a] | 1 |
| Tetrarogidae | *Notesthes robusta* | Bullrout | 563 |

[a] Economically important.

the angle of attack). Total system contact (m) was calculated as the sum of the mean predicted foot-rope (wind-end spread) and otter-board contacts, and the sled baseplates for the triple- and quad-rigs.

At the end of each deployment, the catches from each trawl within each configuration were separated into school prawns and total bycatch, and weighed. For the double-, triple- and quad-rigs, catches within the above two categories from each trawl were then combined, and the numbers of each bycatch species, and total lengths (TL in mm) of the most abundant teleosts recorded (i.e. from the total catch of the trawl configuration). Random samples of ~800 g of school prawns from each deployment were placed into plastic bags and transferred to the laboratory, where at least 200 individuals were measured (carapace length – CL in mm), weighed and counted. These latter data were used to estimate the total number, number per 500 g (a local industry measure; Broadhurst and Millar, 2009) and mean CL caught from each trawl configuration, during each deployment.

The hypothesis of no differences in mesh sizes between the various trawl bodies, extensions and the codends was tested using a linear model (LM). The remaining technical and biological data were analysed in linear mixed models (LMM), with some standardised prior to analyses. The weights of school prawns and total bycatch from each trawl in each configuration were log-transformed (so that effects would act multiplicatively) and analysed as 'absolute' catches per 35-min deployment. The raw data were also standardised to per ha trawled (using the swept area between the wing-ends and the distance trawled) and then log-transformed. For double-, triple- and quad-rigs, data for all catches were also pooled across trawls, and treated as above, but with standardisation to per ha trawled using the cumulative (total) wing-end spread of the entire trawl configuration. The remaining data (including mean CL and number of school prawns per 500 g, drag, wing-end spread, SOG, distance trawled, and fuel consumed) were analysed in their raw form.

Linear mixed models were fitted to explain variability among responses describing the performance of trawls (i) within double-, triple- and quad-rigs and also (ii) the total trawl configurations (i.e. pooled across trawls). The within-system LMMs (i above) were restricted to 'trawls' as a fixed factor, and 'days' and 'deployments' as random factors. The LMMs assessing the performances of the total trawl configurations (ii above) included 'trawl configuration' as fixed while days and 'blocks' (i.e. each day/trawl configuration combination) were included as random terms. In an attempt to more closely explain variability among total trawl configuration wing-end spread, drag, and fuel consumption, additional covariates, including SOG, 'flow' (calculated as the speed of the current in the direction of travel and defined as SOG–STW), distance aft of the trawl configuration from the vessel and fishing depth were also included.

All models were fitted using the lmer function from the lme4 package of the R statistical language and the significance of trawl configuration determined using a likelihood ratio test (LRT). Where competing models were assessed, the most parsimonious was chosen based on the lowest value for a penalised log-likelihood in the form of Akaike's information criterion. Significant differences detected for the main effect of trawl configuration were subsequently explored using pairwise comparisons between the four configurations in conjunction with the Benjamini–Hochberg–Yekutieli procedure to control the false discovery rate (FDR; Benjamini and Yekutieli, 2001). Size-frequency data for school prawns and key fish were pooled, plotted and graphed.

## 3. Results

Over 24 days of fishing, 36 deployments of each trawl configuration were completed, catching ~953 and 287 kg of school prawns and bycatch, respectively (Table 2). The bycatch comprised 25 species, although more than 95% of the total (by number) were forktail catfish, *Arius graeffei* (73.8%), yellowfin bream, *Acanthopagrus australis* (7.3%), narrow banded sole, *Synclidopus macleayanus* (4.6%), bullrout, *Notesthes robusta* (4.0%), silver biddy, *Gerres subfasciatus* (3.5%) and mulloway, *Argyrosomus japonicus* (2.2%) (Table 2).

Technical data were collected for all replicate deployments except three of the quad rig on the last day, during which one of the transducers failed. These latter deployments were excluded from analyses for standardised (per ha) catches.

*3.1. Engineering performances*

There were no significant differences in SMO between the trawl bodies (overall mean ± SE of 42.48 ± 0.09 mm), extensions (41.40 ± 0.17 mm) or codends (27.35 ± 0.07 mm) (LM, $p > 0.05$). The total system weights of the single-, double-, triple- and quad-rigs were 247.92, 239.06, 262.96 and 279.36 kg, respectively, while the total twine areas creating drag were 8.87, 6.62, 7.07 and 7.20 $m^2$ (Table 1). Otter-board (and sled) areas were calculated at 2.90, 2.98, 1.33 and 1.88 $m^2$, respectively providing total system areas of 12.67, 10.73, 9.78 and 10.68 $m^2$ (Table 1).

Despite attempts at maintaining comparable SOG among trawl configurations (via adjustments to engine output) there was a significant effect of gear configuration (LMM, $p < 0.001$; Tables 3 and 4), with subsequent FDR pair-wise comparisons revealing that double rig was towed at a slightly, but nevertheless significantly, lower SOG ($p < 0.01$, by between 4 and 6%), than the single-, triple- and quad-rigs; all of which had the same SOG ($p > 0.05$; Tables 3 and 4). Because all deployments were 35 min and encompassed the same spatial conditions, the observed differences in SOG were reflected in the distances travelled ($p < 0.001$; Tables 3 and 4).

The LMMs also detected significant main effects (or interactions with covariates) of trawl configuration on both within system (i.e. for double-, triple- and quad-rigs) and total wing-end spreads, drag, and fuel consumed per 35-min deployment and per ha trawled ($p < 0.001$; Tables 3 and 4). For the double rig, the port trawl had significantly less predicted mean spread than the starboard trawl, and the same occurred for the combined spread of the two trawls on each side of the quad rig (LMM $p < 0.001$). The predicted mean wing-end spread of the centre trawl of the triple rig was significantly less than the average wing-end spread of the two outer trawls (LMM, $p < 0.001$). The predicted wing-end spreads were used to calculate otter board angles of attack of ~28.70°, 33.10°, 33.10° and 35.50° for the single-, double-, triple- and quad-rigs, and total system contacts of 11.08, 12.73, 12.44 and 13.23 m, respectively (Table 4).

In terms of total wing-end spread, and in addition to the trawl effects previously described, the most parsimonious LMM included a main effect of SOG ($p < 0.001$) and an interaction between trawl configuration and flow ($p < 0.01$), manifesting as a trend of increasing spread with SOG (0.30 m per 1 $m\,s^{-1}$) and decreasing spread with flow (between −0.27 and −0.001 m per 1 $m\,s^{-1}$), respectively that was more strongly evident for single- and double-rigs. False discovery rate pair-wise comparisons of the main effect of trawl configuration (irrespective of flow) revealed no significant differences between the total predicted mean wing-end spreads of triple- (a headline-to-wing-end 'spread ratio' – SR of 75.46%) and quad-rigs (74.37% SR) ($p > 0.05$), but both were significantly, and incrementally greater than double- (68.76% SR) and single-rigs (63.50% SR) ($p < 0.001$; Tables 3 and 4).

**Table 3**
Summaries of likelihood ratio test (LRT) statistics from linear mixed models assessing the importance of the fixed effect of trawl configuration (single-, double-, triple- and quad-rigs) in explaining variability among technical and biological responses, and false-discovery-rate (FDR) adjusted paired comparisons of significant differences among gears. Numbers and weights were analysed as absolute (per 35-min deployment) and also standardised to per ha trawled, calculated using the total average wing-end spread (per deployment) and then log-transformed.

| | LRT | FDR |
|---|---|---|
| Technical variables | | |
| Speed across the ground | 41.75*** | Single = triple = quad > double |
| Distance trawled | 23.45*** | Single = triple = quad > double |
| Total wing-end spread | 140.56*** | Single < double < triple = quad |
| Drag | 81.87*** | Single > double > triple = quad |
| Fuel | | |
| $L\,h^{-1}$ | 88.68*** | Single > double > triple = quad |
| $L\,ha^{-1}$ | 86.53*** | Single > double > quad > triple |
| Biological variables | | |
| Wt of school prawns | | |
| 35-$min^{-1}$ | 8.41* | Single < quad; all others equal |
| $Ha^{-1}$ | 5.86 | |
| No. of school prawns | | |
| 35-$min^{-1}$ | 9.69* | Single < quad; all others equal |
| $Ha^{-1}$ | 7.00 | |
| Mean CL of school prawns | 13.93** | Single > double = triple = quad |
| No. of school prawns 500 $g^{-1}$ | 13.53** | Single < double = triple = quad |
| Wt of total by catch | | |
| 35-$min^{-1}$ | 5.16 | |
| $Ha^{-1}$ | 8.17* | Single > triple; all others equal |
| No. of total bycatch | | |
| 35-$min^{-1}$ | 3.69 | |
| $Ha^{-1}$ | 1.24 | |
| No. of forktail catfish | | |
| 35-$min^{-1}$ | 5.29 | |
| $Ha^{-1}$ | 3.63 | |
| No. of yellowfin bream | | |
| 35-$min^{-1}$ | 9.82* | Single > double = triple = quad |
| $Ha^{-1}$ | 11.63** | Single > double = triple = quad |
| No. of narrow banded sole | | |
| 35-$min^{-1}$ | 5.52 | |
| $Ha^{-1}$ | 3.29 | |
| No. of bullrout | | |
| 35-$min^{-1}$ | 7.20 | |
| $Ha^{-1}$ | 4.73 | |
| No. of silver biddy | | |
| 35-$min^{-1}$ | 4.61 | |
| $Ha^{-1}$ | 4.70 | |
| No. of mulloway | | |
| 35-$min^{-1}$ | 4.35 | |
| $Ha^{-1}$ | 4.00 | |

* $p < 0.05$.
** $p < 0.01$.
*** $p < 0.001$.

**Table 4**
Summary of selected performance and environmental impact indicators for single-, double-, triple- and quad-rigs. Where appropriate the predicted means (±SE) are provided. Spread ratio was calculated as (total wing-end spread ÷ total headline length) × 100. Total system contact was calculated as the sum of the mean predicted foot-rope (wind-end spread) and otter-board contacts, and the sled baseplates for the triple- and quad-rigs.

| Variable | Single | Double | Triple | Quad |
|---|---|---|---|---|
| Engine output (rpm) | 1900 | 1850 | 1850 | 1800 |
| SOG ($m\,s^{-1}$) | 1.28 ± 0.02 | 1.18 ± 0.02 | 1.28 ± 0.02 | 1.25 ± 0.02 |
| Distance trawled (km) | 2.72 ± 0.04 | 2.52 ± 0.04 | 2.69 ± 0.04 | 2.63 ± 0.04 |
| Total wind-end spread (m) | 9.29 ± 0.10 | 10.06 ± 0.08 | 11.04 ± 0.09 | 10.88 ± 0.09 |
| Total spread ratio (%) | 63.50 | 68.76 | 75.46 | 74.37 |
| Predicted otter board angle of attack | 28.70 | 33.10 | 33.10 | 35.50 |
| Total system contact (m) | 11.08 | 12.73 | 12.44 | 13.23 |
| Drag (kgf) | 571.65 ± 4.91 | 532.36 ± 4.36 | 509.08 ± 4.57 | 516.62 ± 4.55 |
| Fuel | | | | |
| $L\,h^{-1}$ | 12.33 ± 0.09 | 11.25 ± 0.09 | 10.65 ± 0.09 | 10.82 ± 0.09 |
| $L\,ha^{-1}$ | 2.88 ± 0.02 | 2.44 ± 0.02 | 2.13 ± 0.02 | 2.21 ± 0.02 |

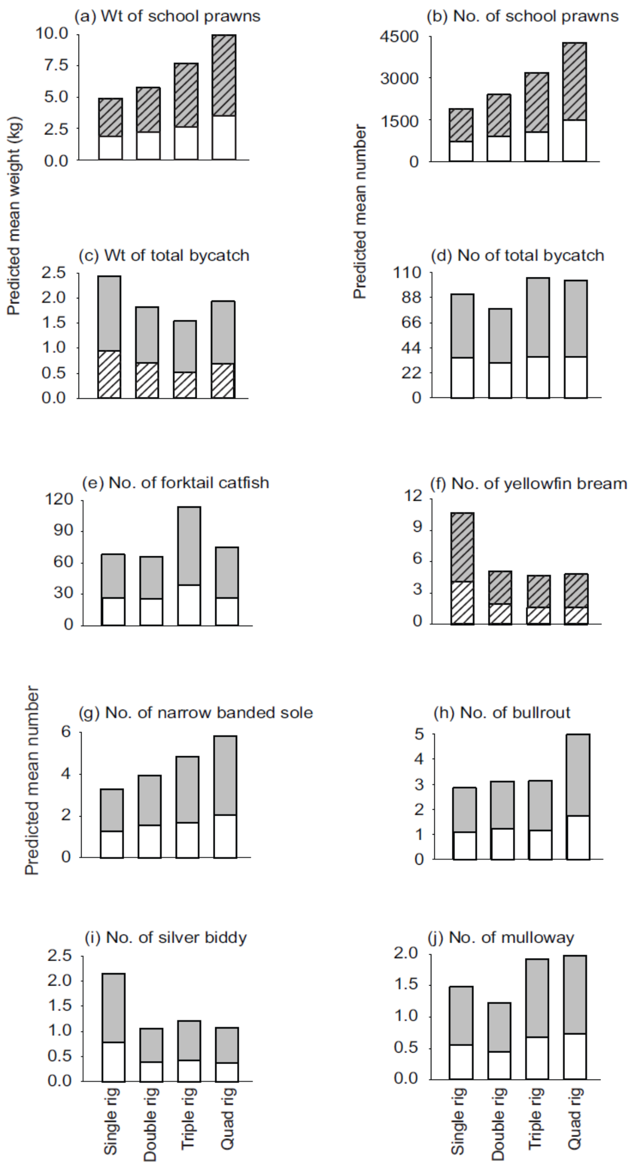


**Fig. 3.** Differences in predicted absolute (per 35-min deployment – grey histograms) and standardised (per ha trawled – white histograms) mean catches between the single-, double-, triple- and quad-rigs for the (a) weights and (b) numbers of school prawns, *Metapenaeus macleayi*, (c) weights and (d) numbers of total bycatch, and numbers of (e) forktail catfish, *Arius graeffei*, (f) yellowfin bream, *Acanthopagrus australis*, (g) narrow banded sole, *Synclidopus macleayanus*, (h) bullrout, *Notesthes robusta*, (i) silver biddy, *Gerres subfasciatus*, and (j) mulloway, *Argyrosomus japonicus*. Diagonal parallel lines represent significant likelihood ratio test statistics detected in linear mixed models.

The most parsimonious LMM explaining drag was restricted to the random terms and the fixed main effects of trawl configuration and flow. The latter manifested as a positive relationship with drag (irrespective of the trawl configuration), while FDRs revealed that the triple- and quad-rigs had similar (non-significant, $p > 0.05$) drags, that were significantly and incrementally less than the single- and double-rigs by up to 10.95 and 4.37%, respectively ($p < 0.001$; Tables 3 and 4).

The total fuel used followed the same trend as drag (but with a significant main effect of SOG, LMM, $p < 0.001$), with no significant differences in predicted mean L per hour (using the average distance of 2.64 km trawled per deployment) between triple- and

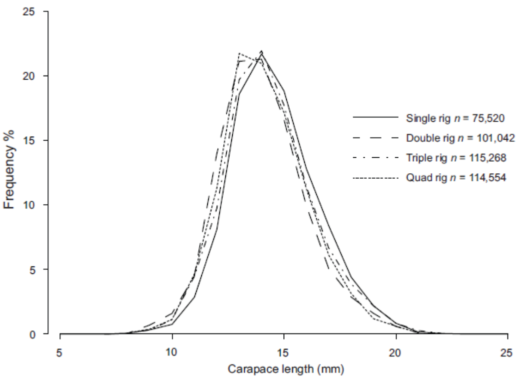


**Fig. 4.** Size-frequency distributions for school prawns, *Metapenaeus macleayi* caught by the four trawl configurations.

quad-rigs (FDR, $p > 0.05$); both of which required significantly less fuel than double- (by 5.4 and 3.75%, respectively) and single-rigs (by 13.65 and 12.21%) (FDR, $p < 0.01$; Tables 3 and 4). Double rig also required significantly less fuel (8.71%) than the single rig (FDR, $p < 0.05$; Tables 3 and 4). In terms of fuel used per ha trawled, there were significant incremental reductions between the triple-, quad-, double- and single-rigs (of 3.45, 9.70 and 15.37%) (FDR, $p < 0.05$; Tables 3 and 4).

### 3.2. Catching performances

Significant main effects of trawl were detected within triple- and quad-rigs for the weights of school prawns per 35-min deployment and also per ha trawled (LMM, $p < 0.05$), but not total bycatch (LMM, $p > 0.05$). For the triple rig, compared to the two outside trawls, significantly fewer school prawns were retained in the centre trawl (LMM, $p < 0.05$), probably reflecting the lower spread. The centre trawl also caught a significantly lower weight of school prawns per ha (predicted mean of 2.37 kg) than the two outside trawls (2.80 kg; LMM, $p < 0.001$). For the quad rig, significantly lower predicted mean weights of school prawns per ha were retained in the port (2.23 kg) than starboard pair (2.95 kg; LMM, $p > 0.05$). There were no significant differences in any catches between trawls within the double rig (LMM, $p > 0.05$).

The LMMs assessing the overall performances of each system detected a significant main effect of trawl configuration on the absolute weight and number of school prawns per 35-min deployment, and their mean CL and number per 500 g, the weight of total bycatch per ha trawled, and numbers of yellowfin bream; both per 35-min deployment and ha trawled ($p < 0.05$; Table 3 and Figs. 3a–c, f and 4). False discovery rate pair-wise comparisons revealed that the significant differences in absolute school prawn catches were limited to between the single- and quad-rigs ($p < 0.01$; Table 3 and Fig. 3a). There were no significant differences in the sizes of school prawns among the multi-trawl configurations (FDR, $p > 0.05$; Table 3 and Fig. 4), but the single rig caught significantly fewer smaller individuals (mean predicted CL ± SE and number per 500 g ± SE of 14.68 ± 0.12 mm CL and 191.61 ± 4.98) than the double- (14.34 ± 0.12 mm CL and 206.32 ± 4.98 per 500 g), triple- (14.31 ± 0.12 mm CL and 206.93 ± 4.98 per 500 g) and quad-rigs (14.30 ± 0.12 mm CL and 207.56 ± 4.98 per 500 g) (FDR, $p < 0.01$) (Fig. 4).

Compared to the single rig, the triple rig retained a significantly lower weight of total bycatch per ha (FDR, $p < 0.05$; Table 3, Fig. 3d) and all three multi-trawl rigs caught significantly fewer yellowfin bream (FDR, $p < 0.05$; Table 3 and Fig. 3f – predicted means reduced by 64.67–78.26%), particularly those that were larger (Fig. 5). There were no other effects on any teleosts, including sizes of the most abundant species (forktail catfish) (Fig. 5).

## 4. Discussion

This study identified clear and significant differences in engineering and catching performances among the four penaeid-trawl configurations, with incremental magnitudes of improvement broadly decreasing with an increasing number of nets. The relative inter-configuration performances need to be discussed with respect to the likely influence of several complex, interacting and confounding factors. Attempting to detangle the key variables facilitates some insight (beyond the current study) into appropriate refinements to penaeid-trawl configurations to reduce associated environmental impacts.

It is important to reiterate that while some characteristics of the trawls and their spreading mechanisms varied among configurations (to similarly match the size of the trawler and maximise performance), wherever possible the rigs were tightly standardised. For example, beyond identical mesh, knot orientations, materials and overall headline length, all trawls had the same cumulative sweep length (9.76 m), and the individual distances between wing-ends and otter boards or sleds were representative of common configurations and sufficient to ensure that no debris (e.g. weed) was directed into the trawls, which could potentially confound drag (Broadhurst et al., 2012b). Also, all trawls had identical ground gear and therefore relative contributions to total system drags (including similar contact pressures), were deployed within the same temporal and spatial boundaries (i.e. flat sand substratum), and attained SRs within the range typically observed for such configurations used throughout Australia and overseas (Sterling, 2005). Lastly, while there was some inadvertent confounding effect of speed (i.e. the double rig was towed slightly slower than the other configurations), the relevant LMMs adjusted wing-end spread and drag accordingly.

Given the above, the observed inter-configuration variability in engineering performances can be almost entirely attributed to the remaining key system differences of total twine and otter-board areas. Previous studies support such a relationship, with these components contributing up to ~70 and 35% respectively of the total system drag–depending on the configuration (Priour, 2009; Sterling and Eayrs, 2010).

The interactive effects of twine and otter-board areas on drag and wing-end spread can be coarsely illustrated by their relative contributions towards total system areas. For example, the long (12.64 m) single-trawl configuration had both the greatest twine and otter-board areas, and therefore the most drag. It also had the least wing-end spread (~64% SR). Substituting this configuration for double rig with two 50%-shorter trawls resulted in the lowest total twine area of all configurations and the concomitant drag benefits. On a per-trawl basis, there was a substantial increase in otter-board area compared to twine area, which raised SR. Conversely, although the twine areas in the triple- and quad-rigs were greater than in the double rig (and there were incremental increases in the surface area because of the additional codends), the sleds and additional towing wires allowed for substantial reductions in otter-board areas. Such an effect concomitantly reduced drag and fuel (by ~18% per ha trawled), while wing-end spread increased by up to ~1 m due to the higher ratio of otter board-to-twine area for each trawl.

It is also important to consider that because the trawls were optimised in terms of their twine areas (i.e. via body

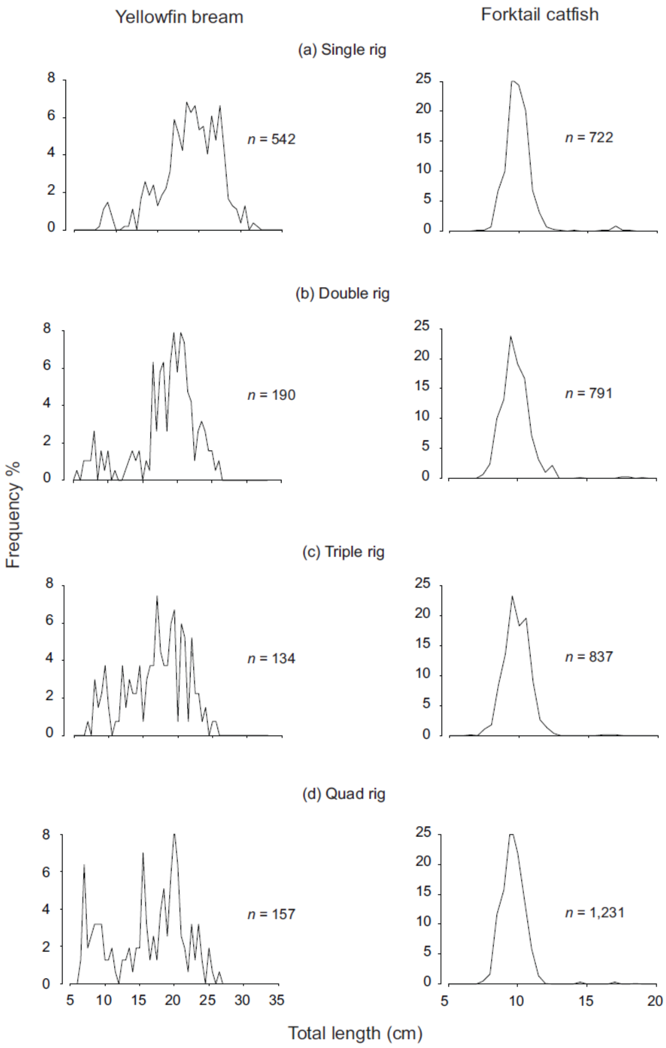


**Fig. 5.** Size-frequency distributions for yellowfin bream, *Acanthopagrus australis* and forktail catfish, *Arius graeffei* caught by the (a) single-, (b) double-, (c) triple- and (d) quad-rigs.

and wing tapers) and associated otter boards (to achieve the required SRs) within the four configurations (Sterling, 2005), the observed relative engineering differences are the minimum that might be expected (Sterling and Eayrs, 2010). As one example, the conventional double-rigged trawls (also 7.32 m headline) used in the Clarence River typically have a body taper of 1N3B (instead of the 1N5B assessed here) and at a towing speed of 1.31 m s$^{-1}$, Broadhurst et al. (2013) reported a mean predicted drag of 624.75 kgf for 3.56 L of fuel per ha trawled. Although not directly comparable (owing to confounding effects of different speeds), at 1.28 m s$^{-1}$ the triple- and quad-rigs had drags and associated fuel consumptions that were at least ~17 and 38% less.

The key mechanisms defining the inter-configuration engineering performances (and particularly the amount of netting as a consequence of trawl length and side taper) described above probably also either directly or indirectly influenced the observed significant differences in the catches of school prawns and yellowfin bream. These impacts can be discussed by considering the known and likely behaviours of both species.

Most penaeids reside close to or in the substratum (especially during the day; Wassenberg and Hill, 1994; Park and Loneragan, 1999), and typically react to trawls by contracting their abdomen in response to tactile stimuli, such as the ground gear, to propel themselves backwards and inadvertently into the trawl at directions depending on their initial orientation (Watson, 1989). After several repeated contractions, many individuals are assumed to impinge against meshes and tumble down the panels and into the codend (Watson, 1989).

Assuming school prawns maintained consistent behaviour, and notwithstanding different SRs, the ground gear of all trawls probably disturbed relatively similar quantities of school prawns per swept area. So the significant difference in catches per 35-min deployment between the single- and quad-rigs, and the non-significant positive relationship of increasing catches with trawl number probably at least partially reflect the greater absolute wing-end spreads. It is conceivable that the otter boards had at least some confounding, ancillary impacts on school prawns entering the trawls (discussed by Broadhurst et al., 2012a, 2013); a conclusion supported by the significant reduction in catches of school prawns per ha for the central trawl (i.e. attached to two sleds instead of otter boards) of the triple rig.

It is also evident, however, that based on the significant reduction in size selectivity (quantified as a smaller mean size and greater number per 500 g) between the single and all multi-rigged trawls and a consistent non-significant reduction in size selectivity with increasing trawl number, at least some of the incremental differences in catches can be explained by relatively greater quantities of small individuals. Such a result could reflect the importance of the wing/trawl-body side taper (Broadhurst et al., 2012b). For example, irrespective of the any variations in the quantity of school prawns entering the trawls, and although similar lateral mesh openings are assumed to have been maintained, the theoretical angle to the flow of netting in the side of the single trawl (~34°) was greater than those in the double- (~33°), triple- (~31°) and quad-rigs (~24°). Combined with the much greater number of meshes (i.e. longer trawl body), any small school prawns passing down the single trawl would have had a greater chance of escaping than from the much shorter, multi-rigged trawls.

Fewer effects were observed for fish, with the only significant difference among configurations limited to yellowfin bream (also affecting the total weight of bycatch)—which was one of the few species caught in any abundance. In terms of absolute and standardised catches, the single gear caught more yellowfin bream (biased towards larger fish) than the multi-trawl rigs, which may reflect either the relatively (i) longer (Engås and Godø, 1989; Andrew et al., 1991) and/or (iii) shallower-angled sweeps (Sangster and Breen, 1998); (ii) larger otter boards and associated higher headline height (von Szalay and Somerton, 2005); and/or (iii) longer trawl body (Broadhurst et al., 2012b).

Sweeps are known to have species-specific effects on teleosts (Engås and Godø, 1989; Andrew et al., 1991) and, along with high headline height (which can improve catches, if any increase coincides with the vertical distribution of fish) are integral components for herding fish into trawls. Such characteristics may have increased the numbers of yellowfin bream entering the single trawl. Equally likely, once in this trawl, relatively fewer yellowfin bream could have escaped than from the shorter multi-trawl rigs. Broadhurst et al. (2012b) also observed relatively greater catches of another local schooling species (southern herring, *Herklotsichthys castelnaui*) in longer than shorter (double-rigged) penaeid trawls, and concluded that more individuals probably escaped either from the mouth of the latter trawls during haul back (Watson, 1989), or reached the Nordmøre-grid more quickly and had sufficient energy to actively swim through the exit. Further, owing to a positive relationship between size and swimming capacity (Beamish, 1978), such effects would be expected to be biased towards larger fish (as observed here).

Irrespective of the mechanisms contributing towards the greater catches of yellowfin bream in the single rig, there were no concomitant effects on any other teleosts. Such species-specific behavioural responses are common (Andrew et al., 1991). For example, Broadhurst et al. (2013) observed that compared to a double rig, dual-rigged penaeid trawls caught significantly fewer small mulloway; a result attributed to the lack of herding associated with a sled separating trawls (compared to otter boards). These effects were not observed here for the triple- and quad-rigs, but this may reflect the low species diversity and abundance. The only other species caught in appreciable quantities was forktail catfish, and Broadhurst et al. (2013) similarly failed to detect any significant difference in the response of this species to otter boards or a sled. Such differences support ongoing relative assessments of the single-, triple- and quad-rigs during periods of greater abundances of more diverse assemblages of fish.

Notwithstanding the above, it seems that unless there are clear logistical advantages offsetting the relatively greater amounts of fuel required to tow single rig, there is perhaps little point in using this configuration for targeting penaeids. The twine-area savings (and therefore cost of materials) associated with double rig may support the ongoing widespread preferential use of this gear in most fisheries, especially if the drag of otter boards can be simply reduced through innovative design (Sterling and Eayrs, 2010). However, the same technologies would also have relative benefits for triple- and quad-rigs.

These latter two configurations are perhaps the best options for progressing more environmentally benign systems; with the individual choice reflecting key fishery and/or scientific concerns. For example, in terms of habitat impacts, even with the greatest SR compared to the other multi-trawl rigs, triple rig had the lowest otter-board and total system contacts (by 29–55% and 2–6%, respectively). In the absence of more detailed biological data (relative catches), perhaps the choice of triple- or quad-rig would depend on operating conditions. For example, quad rig is often preferred in shallow water, while triple rig is a safer option in deep and/or rough water or with current; primarily because the towing blocks are closer to the vessel centre line (with associated implications for stability) and the trawls can be more easily retrieved after fouling on the seabed because (like single rig) they can be winched up with considerable force without causing any angle of roll.

Irrespective of the choice, a shift from either double- or single- to triple- or quad-rigs requires careful monitoring of effort, since the capacity for greater SRs mean that the latter configurations could increase fishing power (O'Neill and Leigh, 2007). Nevertheless, starting with either triple- or quad-rigs and then attempting to improve their performances by adjusting the plethora of other relevant factors (e.g. otter board profiles and design, body/wing side taper, sweep length, headline height, twine diameter, etc.) known to affect species and/or size selectivity, energy intensities and habitat impacts would seem a coherent strategy for developing more environmentally benign conventional trawling systems.

**Acknowledgements**

This study was funded by the New South Wales (NSW) Department of Primary Industries and the Australian Fisheries Research and Development Corporation (Grant no. 2011/010). Thanks are extended to the (NSW) Professional Fishermen's Association, Steve Everson, Don Johnson, Jen Marshall, Mitch Burns, Chris Barnes, Nick Sarapuk, and especially Craig Brand.

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Fisheries Research 153 (2014) 24–30

Contents lists available at ScienceDirect

Fisheries Research

journal homepage: www.elsevier.com/locate/fishres

# Engineering and catch implications of variable wing-end spread on a penaeid trawl

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ARTICLE INFO

*Article history:*
Received 25 June 2013
Received in revised form 11 October 2013
Accepted 30 December 2013
Handling Editor Dr. P. He
Available online 8 February 2014

*Keywords:*
Bycatch reduction
Drag
Otter trawling
Penaeids
Relative abundance estimates
Spread ratio

ABSTRACT

The importance of wing-end spread on the performance of a generic penaeid trawl was assessed to investigate the potential for confounding effects when comparing modified anterior sections designed to improve selectivity and fuel efficiencies. Two identical beam-and-sled assemblies were configured to allow two identical trawls (7.35 m headlines and footropes) to be adjusted to spread ratios (defined as wing-end spread ÷ headline length) of 0.5, 0.6, 0.7 and 0.8 and deployed ($n = 30$ each) in a double rig across the same depth, current, towing speed and duration. Increasing spread ratio significantly increased drag (by up to 16%), without affecting absolute catch weights. However, when standardised to per ha trawled, significantly fewer targeted school prawns (*Metapenaeus macleayi*) and total bycatch by weight were retained in the wider-spread trawls. The significant reductions in standardised catch with increasing spread ratio were hypothesised to reflect either: (i) slightly reduced ground gear contact and headline heights offsetting the greater swept areas; or perhaps more likely (ii) steeper wing angles which increased the probability of mesh encounters and escape for school prawns and were less efficient for herding fish. Future research comparing modified trawl bodies should focus on maintaining similar spread ratios to minimise confounding effects. Similar logic applies to surveys using penaeid trawls to obtain relative abundance estimates.



## 1. Introduction

Penaeid trawling occurs throughout the inshore waters of >25 tropical and temperate countries around the globe, and is very important to local economies (Vendeville, 1990; Gillett, 2008). While a plethora of trawls and configurations are used, owing to their small mesh sizes (typically 30–50 mm; Vendeville, 1990) and benthic contact, virtually all are characterised by the common key environmental issues of (i) poor size and species selectivity for slow swimming animals (and associated unaccounted fishing mortality) and (ii) high fuel intensity (Kelleher, 2005; Gillett, 2008).

Historical recognition of these two issues has led to various attempts at their resolution (e.g. Sumpton et al., 1989; Andrew et al., 1991; Broadhurst et al., 2000, 2012a,b, 2013a,b). However, by far most relevant work has focused on the first issue and involved retrospectively installing so-called 'bycatch reduction devices' (BRDs) in the posterior sections of trawls (reviewed by Broadhurst, 2000 and Broadhurst et al., 2006). In many cases, BRDs have considerably improved selectivity and reduced unwanted mortalities (Broadhurst et al., 2006), but because the catch comprises only a very small percentage of the total system drag of penaeid trawls there are few, if any, effects on drag (and therefore fuel intensity).

One method by which cumulative improvements in selectivity, along with reductions in drag can be concomitantly addressed is via larger-scale modifications to the anterior sections of penaeid trawls—although this requires understanding of the key influencing factors and their often complex, interactive effects (Sterling, 2005; Broadhurst et al., 2012a,b, 2013a,b). Potentially important factors include, but are not limited to the: number of trawls (i.e. single- or multi-net systems; Andrew et al., 1991; Broadhurst et al., 2013a,b); body and frame-line tapers (Conolly, 1992; Broadhurst et al., 2012b); mesh size, twine diameter and material (Sumpton et al., 1989; Broadhurst et al., 2000); and for otter trawls, sled and otterboard design (Sterling and Eayrs, 2010; Broadhurst et al., 2012a). In many cases, substantial changes to just one of these parameters will concomitantly affect both selectivity and drag.

Because penaeid-trawl systems are dynamic and most are laterally spread by hydrodynamic forces on otter boards, variations to the above parameters often have an ancillary impact on the horizontal opening of the trawl, which can be discussed in relative terms as the 'spread ratio' (wing-end spread ÷ headline length).

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http://dx.doi.org/10.1016/j.fishres.2013.12.018

Depending on the penaeid trawl and spreading mechanism, target spread ratios typically range between 0.50 and 0.85 (Sterling, 2005).

Very little scientific work has been published assessing the effects of spread ratio on penaeid-trawl performance. However, like for other benthic trawls, within any configuration, spread ratio could vary according to a plethora of technical and environmental factors including the towing speed, current, sea conditions, bottom type, warp length and fishing depth (Wathne, 1977; Engås and Godø, 1989; Fujimori et al., 2005; von Szalay and Somerton, 2005; Weinberg and Kotwicki, 2008). Studies with benthic fish trawls have identified that even subtle variations in spread ratio can alter geometry sufficiently to ultimately affect standardised (e.g. per swept area) catches (e.g. Rose and Nunnallee, 1998; von Szalay and Somerton, 2005; Weinberg and Kotwicki, 2008) and drag (Sala et al., 2008). Any similar impacts of spread ratio for penaeid trawls are of concern because these could confound comparisons of conventional and modified anterior sections, thereby making it difficult to ascribe causality to the fixed effects of interest.

Owing to complex interactions of the various factors listed above, isolating spread-ratio effects on trawl catches and drag is very difficult. One method is to use beam-and-sled assemblies and secure trawls at various treatment spread ratios, while keeping all other important parameters as constant as possible. Further, by maintaining the same weight and area of the beam-and-sled assembly, any differences in drag can be directly attributed to spread-ratio effects on trawl geometry. We sought to use this approach at one location in south eastern Australia. Specifically, for a generic, locally used trawl, we replaced the conventional otter boards with a beam-and-sled assembly and tested the hypothesis of no effects of 0.5, 0.6, 0.7 or 0.8 spread ratios on the catches of the targeted penaeids (school prawns, *Metapenaeus macleayi*) and unwanted teleosts and also drag, among similar environmental (depth and substratum) and technical (towing speed, current and warp length) conditions.

## 2. Methods

The work was done during February and March 2013 in Lake Wooloweyah (29°26 S 153°22 E), New South Wales, Australia using a local double-rigged trawler (10 m and 89 kW) fishing in ~2 m across sandy and mud substrata. The trawler had separate winches; each attached to ~80 m of 8 mm diameter–Ø stainless warp and 40 m bridles (6 mm Ø stainless wire). The trawler was equipped with a: global positioning system (GPS; Lowrance); hull-mounted sum log (EchoPilot, Bronze Log+); and load cells and associated data logger (Amalgamated Instrument Company; model no's PA6139 and TP4). The load cells were attached to the bridles (which were always deployed to 12 m) on each side of the vessel to measure their tension.

### 2.1. Trawls, beam assembly and fishing

Two identical conventional trawls were constructed from nominal 41 mm (stretched mesh opening–SMO) mesh (1.25 mm Ø twisted polyethylene-PE twine), and had headlines and footropes that measured 7.35 m (Fig. 1). The headline length and SMO were chosen based on the legislated requirements for this fishery (maximum headline and minimum SMO of 7.50 m and 40 mm respectively). Both trawls were rigged with a single 150 mm Ø float in the centre of the headline and had identical extension sections (100 transversal meshes–*T* × 30 normal meshes–*N* of nominal 41 mm PE mesh, and 2 mm Ø twine) with Nordmøre-grids (28 mm bar spacing) installed and codends (120 × 75 bars–*B*) made from nominal 27 mm polyamide (PA) mesh (1.25 mm Ø twine) hung square (Broadhurst et al., 2012b, Fig. 2). Prior to use, the trawl bodies, extensions and codends were measured (*n* = 15 for each section) for their SMOs using a local purpose-built gauge.

The trawls were deployed behind two independent 6 m long beam-and-sled assemblies on each side of the vessel (Fig. 2a). Each assembly was constructed so that the beams were positioned above the headlines of the trawls on top of the sleds (0.76 × 1.07 m), which could be horizontally positioned and pinned at different widths (3.68, 4.41, 5.15 and 5.88 m) according to the four treatment spread ratios of 0.5, 0.6, 0.7 and 0.8 (effectively providing wing-end angles of 14°, 21°, 29° and 39°; Fig. 2b).

At the start of each fishing day, the sleds on each beam (on each side of the vessel) were adjusted to a different treatment spread ratio and used in three 40 min deployments, after which the trawls were swapped from side-to-side for a further three 40 min deployments. The two load cells were alternated from side-to-side after each deployment. Over ten days, we attempted 30 replicate deployments of the trawls configured to each spread ratio, with an even distribution between sides of the vessel.

### 2.2. Data collected and analyses

The technical data collected during each deployment included the: (i) warp tension (kgF) for each configuration (recorded at 1 min intervals from the load cells); (ii) the total distance (m) trawled (sleds on and off the bottom–obtained from the GPS); and (iii) speed over the ground (SOG) and through the water (STW; both in $ms^{-1}$). The drag of the trawls was assumed through the horizontal component of the tension vector for the warp aft of the vessel. System drag is proportional to warp tension while the declination angle of the warp is constant (i.e. constant warp length and water depth).

Biological data collected at the end of each deployment included the: total weights of school prawns and bycatch; numbers of each bycatch species; and total lengths (TL in mm) of the most abundant teleosts (except forktail catfish, *Arius graeffei*—owing to their spines). Random samples of ~500 g of school prawns were placed into plastic bags and transferred to the laboratory, where they were measured (carapace length–CL in mm), weighed and counted. These latter data were used to estimate the total numbers caught during each deployment.

The hypothesis of no differences in the mesh sizes within the two trawl bodies, extensions or codends was tested in a linear model (LM). Within each experiment, the remaining data were analysed in linear mixed models (LMMs), with some standardised prior to analyses. The numbers and weights of catches were analysed per 40 min deployment, and also standardised to per ha trawled using the swept area of the foot rope (calculated by the known wing-end spread × the distance trawled). In both cases, data were then log-transformed so that predicted effects would be multiplicative. All other data, including the mean CL and the number of school prawns per 500 g (a local industry measure; Broadhurst and Millar, 2009) drag and area and distance trawled were analysed in their raw form.

All LMMs included 'spread ratio' as a fixed effect, while 'trawls', 'sides' and 'days' and the interactions between 'deployments' and days and between sides and days were included as random terms. For the LMM assessing drag, 'load cells' were included as an additional random term while additional fixed covariates included 'SOG', 'STW' and 'flow' (calculated as the speed of the current in the direction of travel and defined as SOG–STW). The most parsimonious model was chosen based on the lowest value for a penalised log-likelihood in the form of the Akaike's information criterion. All models were fitted using either the lmer function from the lme4 package or ASReml in the *R* statistical language, with the significance of spread ratio determined using a Wald *F*. Upon obtaining a significant effect of spread ratio, the differences were subsequently explored using the Benjamini–Hochberg–Yekutieli procedure to

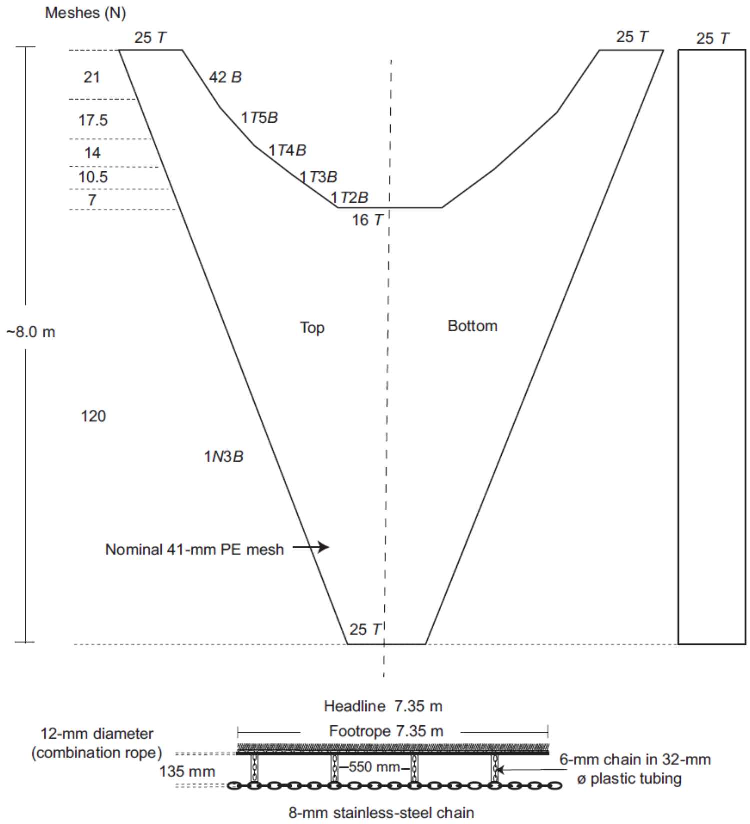


**Fig. 1.** Plan of the penaeid-trawl bodies used in the study. *N*, normals; *T*, transversals; *B*, bars; and Ø, diameter.

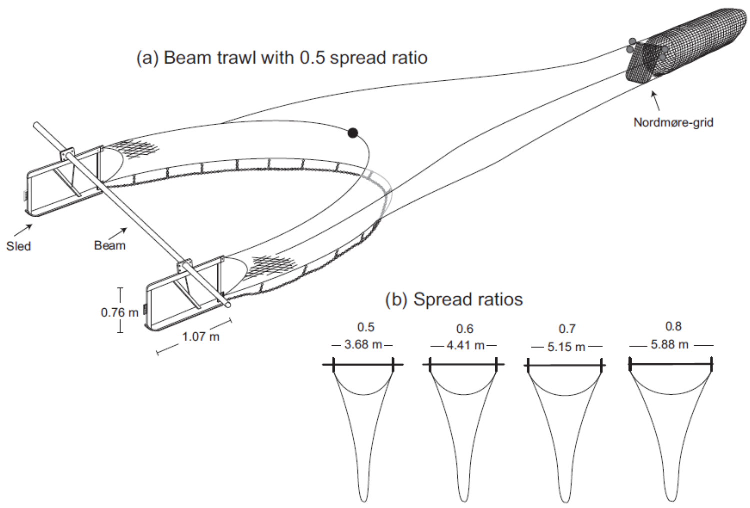


**Fig. 2.** (a) Three-dimensional view of a trawl spread at a ratio of 0.5, and (b) two-dimensional view of the four tested spread ratios and positions of the sleds on the 6 m beam.

**Table 1**
Scientific and common names and numbers of organisms caught during the experiment.

| Family | Scientific name | Common name | Numbers |
|---|---|---|---|
| *Crustaceans* | | | |
| Penaeidae | *Metapenaeus macleayi* | School prawn | 119, 235 |
| | *Penaeus monodon* | Tiger prawn | 10 |
| Palaemonidae | *Macrobrachium novaehollandiae* | Freshwater prawn | 37 |
| Portunidae | *Scylla serrata* | Mud crab | 4 |
| *Teleosts* | | | |
| Ambassidae | *Ambassis jacksoniensis* | Port Jackson glassfish | 7394 |
| | *Ambassis marianus* | Ramsey's perchlet | 1034 |
| Ariidae | *Arius graeffei* | Forktail catfish | 1952 |
| Apogonidae | *Siphamia roseigaster* | Pink-breasted siphonfish | 87 |
| Carangidae | *Pseudocaranx dentex* | Silver trevally | 14 |
| | *Scomberoides commersonnianus* | Queenfish | 1 |
| | *Trachurus novaezelandiae* | Yellowtail scad | 1 |
| Clupeidae | *Herklotsichthys castelnaui* | Southern herring | 4939 |
| | *Hyperlophus vittatus* | Whitebait | 2552 |
| Dasyatididae | *Dasyatis* sp | Stingray | 18 |
| Dinolestidae | *Dinolestes lewini* | Long-finned pike | 1 |
| Eleotrinae | *Gobiomorphus australis* | Striped gudgeon | 3 |
| Elopidae | *Elops hawaiensis* | Giant herring | 3 |
| Engraulidae | *Engraulis australis* | Australian anchovy | 21 |
| Enoplosidae | *Enoplosus armatus* | Old wife | 37 |
| Gerreidae | *Gerres subfasciatus* | Silver biddy | 675 |
| Gobiidae | *Arenigobius bifrenatus* | Bridled goby | 6 |
| Hemiramphidae | *Hyporhamphus regularis* | River garfish | 23 |
| Megalopidae | *Megalops cyprinoides* | Oxeye herring | 2 |
| Mugilidae | *Mugil cephalus* | Bully mullet | 93 |
| | *Liza argentea* | Flat-tail mullet | 18 |
| Muraenesocidae | *Muraenesox bagio* | Common pike eel | 4 |
| Monodactylidae | *Monodactylus argenteus* | Diamond fish | 131 |
| Paralichthyidae | *Pseudorhombus arsius* | Largetooth flounder | 3 |
| Percichthyidae | *Macquaria novemaculeata* | Australian bass | 1 |
| Platycephalidae | *Platycephalus fuscus* | Dusky flathead | 3 |
| Plotosidae | *Euristhmus lepturus* | Longtail catfish | 47 |
| Pomatomidae | *Pomatomus saltatrix* | Tailor | 834 |
| Sciaenidae | *Argyrosomus japonicus* | Mulloway | 219 |
| Sillaginidae | *Sillago ciliata* | Sand whiting | 1 |
| Soleidae | *Synclidopus macleayanus* | Narrow banded sole | 18 |
| Sparidae | *Acanthopagrus australis* | Yellowfin bream | 1332 |
| | *Rhabdosargus sarba* | Tarwhine | 3 |
| Terapontidae | *Pelates quadrilineatus* | Trumpeter | 11 |
| Tetraodontidae | *Tetractenos glaber* | Toadfish | 16 |
| Tetrarogidae | *Centropogon australis* | Fortescue | 3 |
| | *Notesthes robusta* | Bullrout | 8 |

control the false discovery rate (FDR; Benjamini and Yekutieli, 2001) for multiple pair-wise comparisons.

## 3. Results

Thirty deployments were successfully completed for each of the 0.5, 0.6 and 0.7 spread ratios, while one deployment for the 0.8 spread ratio was fouled and excluded from analyses. All trawl bodies were free of meshed fish and debris. Catches from the 119 deployments comprised 316 and 120 kg of school prawns (6–24 mm CL) and bycatch, respectively. More than 40 bycatch species were caught, but 89% of the total comprised Port Jackson glass fish, *Ambassis jacksoniensis* (34%; 1.5–7.0 cm TL), southern herring, *Herklotsichthys castelnaui* (23%; 4.0–18.0 cm TL), whitebait, *Hyperlophus vittatus* (12%; 2.0–9.0 cm TL), forktail catfish (9%; $<\sim 15$ cm TL), yellowfin bream, *Acanthopagrus australis* (6%; 5.0–23.0 cm TL) and Ramsey's perchlet, *Ambassis marianus* (5%; 5.5–9.5 cm TL) (Table 1). Analyses were restricted to these species.

### 3.1. Engineering aspects

There were no significant differences in SMOs between the two tested trawl bodies, extensions or codends, with combined means ±SE of 41.33 ± 0.10, 41.50 ± 0.24 mm, and 27.37 ± 0.10 mm, respectively (LM, $p > 0.05$). The four spread ratios were all tested at very similar SOGs and STWs (overall means ± SEs of 1.34 ± 0.002 and 1.36 ± 0.002 $ms^{-1}$, respectively and with virtually no flow), which resulted in no significant difference in the distances trawled (ranging between 3.0 and 3.4 km; LMM, $p > 0.05$; Table 2). However, as expected the areas trawled were significantly different and positively associated with spread ratio, with predicted means ±SE of 1.25 ± 0.02, 1.50 ± 0.02, 1.75 ± 0.02 and 1.99 ± 0.02 ha, respectively; LMM and FDR, $p < 0.01$; Table 2).

The most parsimonious model for drag comprised all random effects and the fixed effects of spread ratio and STW; both of which were significant, with the latter having a strong positive effect on drag (LMM, $p < 0.001$; Table 2). The relationship between spread ratio and drag was also broadly positive. Specifically, using a centred (average) STW, the predicted mean drags ±SE for the 0.5, 0.6, 0.7 and 0.8, spread ratios were 149.83 ± 6.66, 162.85 ± 6.66, 161.95 ± 6.66 and 178.25 ± 6.68 kgF, respectively, with significant differences among all pair-wise differences (FDR, $p < 0.01$), except the 0.6 and 0.7 spread ratios (FDR, $p > 0.05$).

### 3.2. Catching performances

Linear mixed models detected significant effects of spread ratio on the numbers of school prawns per 40 min deployment and per 500 g, and the number and weight per ha trawled, along with the weight of total bycatch per ha trawled ($p < 0.05$; Table 2 and

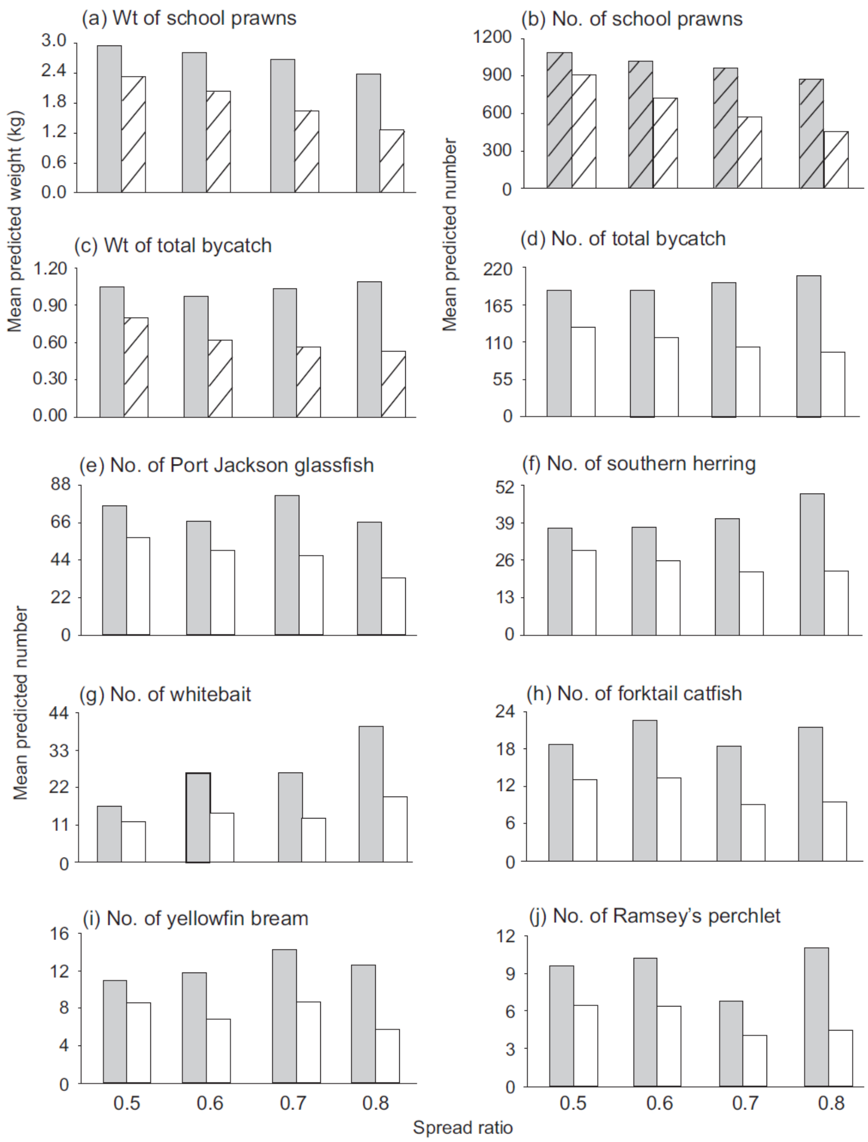


**Fig. 3.** Differences in back-transformed predicted absolute (per 40 min deployment–gray bar plot) and standardized (per ha trawled–white bar plot) mean catches between the 0.5, 0.6, 0.7 and 0.8 spread ratios for the (a) weights and (b) numbers of school prawns, *Metapenaeus macleayi*, (c) weights and (d) numbers of total bycatch, and numbers of (e) Port Jackson glassfish, *Ambassis jacksoniensis*, (f) southern herring, *Herklotsichthys castelnaui*, (g) whitebait, *Hyperlophus vittatus*, (h) forktail catfish, *Arius graeffei*, (i) yellowfin bream, *Acanthopagrus australis*, and (j) Ramsey's perchlet, *Ambassis marianus*. Oblique lines indicate significant Wald *F*-values detected in linear mixed models ($p < 0.05$).

Fig. 3a–c and Fig. 4). False discovery rate pair-wise comparisons revealed that both the numbers and weights of school prawns per ha trawled were significantly lower with increasing spread ratio (by between 20–51% relative to the 0.5 spread ratio; $p < 0.05$; Table 2 and Fig. 3a and b). There was evidence that these broad incremental reductions in standardised catches of school prawns were more prevalent for smaller sizes, with predicted mean CL and numbers per 500 g (±SE) that generally increased and decreased, respectively with increasing spread ratio (Fig. 4). However, FDRs did not separate the significant main effect of spread ratio for the latter variable ($p > 0.05$, Table 2 and Fig. 4). Similarly, FDRs did not separate differences among spread ratios for the numbers of

**Table 2**
Summaries of Wald *F*-values from linear mixed models assessing the significance of spread ratio on technical and biological parameters, and false-discovery-rate (FDR) adjusted paired comparisons of significant differences. Numbers (excluding school prawns per 500 g) and weights were analysed un-standardised (i.e. per 40 min deployment) and standardised to per ha trawled, calculated using the known wing-end spread (per deployment) and then log-transformed.

| | *Wald F* | FDR |
|---|---|---|
| Technical variables | | |
| Distance trawled | 1.04 | – |
| Hectare trawled | $3529^{***}$ | 0.5 < 0.6 < 0.7 < 0.8 |
| Drag | $5.59^{**}$ | 0.5 < 0.6 = 0.7 < 0.8 |
| Biological variables | | |
| Wt. of school prawns | 2.61 | – |
| Wt. of school prawns $ha^{-1}$ | $36.81^{**}$ | 0.5 > 0.6 > 0.7 > 0.8 |
| No. of school prawns | $5.05^{*}$ | Not separated |
| No. of school prawns $ha^{-1}$ | $38.98^{**}$ | 0.5 > 0.6 > 0.7 > 0.8 |
| Mean CL of school prawns | 1.77 | – |
| Number of school prawns per 500 g | $3.00^{*}$ | Not separated |
| Wt. of bycatch | 2.14 | – |
| Wt. of bycatch $ha^{-1}$ | $6.13^{**}$ | 0.5 > 0.6 = 0.7 = 0.8 |
| No. of bycatch | 1.13 | – |
| No. of bycatch $ha^{-1}$ | 2.38 | – |
| No. of Port Jackson perchlet | 0.16 | – |
| No. of Port Jackson perchlet $ha^{-1}$ | 2.47 | – |
| No. of southern herring | 1.18 | – |
| No. of southern herring $ha^{-1}$ | 1.26 | – |
| No. of whitebait | 2.47 | – |
| No. of whitebait $ha^{-1}$ | 1.56 | – |
| No. of forktail catfish | 0.36 | – |
| No. of forktail catfish $ha^{-1}$ | 1.39 | – |
| No. of yellowfin bream | 0.20 | – |
| No. of yellowfin bream $ha^{-1}$ | 0.27 | – |
| No. of Ramsey's perchlet | 0.35 | – |
| No. of Ramsey's perchlet $ha^{-1}$ | 0.85 | – |

* $p < 0.05$.
** $p < 0.01$.
*** $p < 0.001$.

school prawns per 40 min deployment, although the means followed the same trend as the standardised catches ($p > 0.05$, Table 2 and Fig. 3a).

Compared to the 0.5 spread ratio, all other spread ratios caught significantly (and similarly) less total bycatch per ha by weight (by 25–30%, FDR $p < 0.01$; Table 2 and Fig. 3c). There were no other significant differences between individual species of fish (Table 2 and Fig. 3e–j).

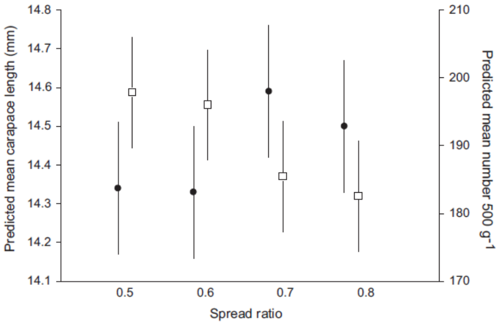


**Fig. 4.** Predicted mean (±SE) carapace length in mm (circles) and number of school prawns per 500 g (squares) retained by the trawls spread at ratios of 0.5, 0.6, 0.7 and 0.8.

## 4. Discussion

Despite resulting in considerably greater swept areas (by up to 1.6 times), increasing spread ratio did not significantly improve the catching efficiency of the assessed trawls for either the targeted penaeids or non-targeted organisms. On the contrary, drag generally increased and, when catches were standardised to per ha trawled, there was a clear negative relationship between spread ratio and efficiency for school prawns, and a comparable trend for the weight of bycatch. The likelihood that such poorer standardised catch were caused by either (i) fewer relevant organisms entering (per ha) and/or (ii) more escaping from the wider-spread trawls can be discussed in terms of possible gear geometry and species-specific behaviour. This information can then be used to make recommendations concerning the biological and engineering optimisation of penaeid trawls.

In terms of fewer organisms entering the wider-spread trawls (per ha), one possible explanation might involve a subtle concomitant reduction in vertical trawl opening. Specifically, studies with fish trawls have shown that the lateral tension evoked by increasing spread ratio can reduce both headline height and ground-gear contact (Rose and Nunnallee, 1998; von Szalay and Somerton, 2005). While the design of the trawls tested here and their configuration (i.e. no sweeps) might limit major changes in vertical fishing height, the potential exists for some reduction in ground-chain pressure on the lake bottom. Like most penaeids, school prawns remain buried or very close to the substratum during the day (Ruello, 1973; Coles, 1979; Wassenberg and Hill, 1994). The typical response of penaeids to trawls appears mostly limited to tactile stimuli and, more specifically, after initial contact from the ground chain they contract their abdomen and propel themselves backwards, often into the trawl mouth (Watson, 1989). Even a slight reduction in the weight of the ground chain on the bottom associated with increasing spread ratio could account for the fewer catches.

Any changes to the trawl opening could also explain the significant reduction in standardised weight of bycatch by the 0.6, 0.7 and 0.8 spread ratios, compared to the 0.5. For example, while any changes in ground gear pressure were probably insufficient to allow fish to pass under the trawl, even a slight reduction in headline height might have facilitated their vertical escape (Rose and Nunnallee, 1998). Perhaps more likely, the wider-angled wings (which would have increased from ~14° in the 0.5 to almost 40° in the 0.8) may have been less effective at herding some fish into the trawl (Rose and Nunnallee, 1998; von Szalay and Somerton, 2005).

Notwithstanding the above, and although unlikely, the beam may have had a homogenous, confounding impact on fish. Unlike penaeids, which remain in or close to the substratum, and not withstanding species-specific differences (e.g. Broadhurst et al., 1996), teleosts are physiologically better equipped to actively respond to approaching trawls (Watson, 1989). Although the beam was positioned above and immediately anterior to the headline, it may have provided sufficient visual stimuli to evoke an escape response in some individuals away from the trawl (Broadhurst et al., 2012a). We suggested the potential for such effects in an earlier study, but these were limited to southern herring; the escape of which may have been exacerbated by a relatively lower, less hydrodynamic beam than that used here (Broadhurst et al., 2012a).

While the trawl geometry described above could account for some of the observed reductions in catching efficiency (especially for fish) with increasing spread ratio, some individuals probably escaped thorough the trawl meshes. For example, the size range of the school prawns (6–24 mm CL) means that all could have easily fit through the legally required 41 mm mesh. As spread ratio increased, so to would the probability and normal collision angle of school prawns through the sides of the trawl. The bias toward fewer small prawns in the wider-spread trawls may support such a theory. This process may also have extended to some fish, since individuals of several species, and especially whitebait (all <9 cm TL) and Port Jackson glassfish (<7 cm TL), were small enough to pass through the 41 mm meshes, potentially offsetting the greater swept areas of the wider-spread trawls.

Irrespective of the underlying causes of catch differences among spread ratios, the results have implications for the on-going testing of modifications to anterior penaeid sections. First, it is clear that the mesh size needs to be optimised for the desired sizes of the targeted species. The large mesh size in the trawl body relative to the sizes of school prawns targeted in Lake Wooloweyah means that even slight variations in lateral mesh opening and/or contact angle/probability as a consequence of different spread ratios could have an impact, potentially confounding comparisons of modified anterior sections. The implications of this result also have broader relevance, given that irrespective of the fishery there typically is a wide size range of penaeids available for capture, including individuals smaller than the maximum lateral mesh openings in the trawl body (e.g. Sumpton et al., 1989; Broadhurst et al., 1996).

A second, related issue is that spread ratio needs to be optimised for a particular penaeid-trawl design. As expected, in this study increasing the angle of netting to the towing direction had a generally (albeit highly variable) positive influence on drag, which in terms of absolute trawl efficiency, needs to be offset by at least some compensatory increase in target catches. Within this second theme (and although not a concern here) it is important to recognise that varying spread ratios might evoke other geometric impacts among different penaeid-trawl designs, and especially those with so-called 'lead-a-head' (i.e. when the headline is shorter than the footrope; Wakeford, 1997). Where lead-a-head is used, the relationship with spread ratio is likely to be complex, but could evoke additional variants to absolute catches and efficiency, and therefore warrants formal investigation as part of future research.

Lastly, notwithstanding potential differences among designs, it is clear based on our results that even 10% variations in spread ratio could possibly confound the observed engineering and catching performances of treatment trawls. It seems advisable then to attempt to maintain wing-end spreads as close as possible when comparing modifications and equally importantly, test gears across similar conditions within the same ranges of known influencing environmental (current, sea conditions, bottom type) and technical (towing speed, warp length and fishing depth) parameters.

## Acknowledgements

This study was funded by the New South Wales (NSW) Department of Primary Industries and the Australian Fisheries Research and Development Corporation (Grant no. 2011/010). Thanks are extended to the (NSW) Professional Fishermen's Association, Steve Everson, Don Johnson, Jen Marshall, Mitch Burns, Chris Barnes, Nick Sarapuk, and especially Craig Brand.

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Fisheries Management and Ecology

*Fisheries Management and Ecology*, 2014, 21, 299–311

# Comparing and modifying penaeid beam and otter trawls to improve ecological efficiencies

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**Abstract** In an attempt to improve the selectivity and engineering performances of generic penaeid trawls, three established and one novel spreading-mechanism configurations were assessed: otter boards attached (1) with and (2) without 3.15-m sweeps to a 7.35-m headline trawl, and a beam rigged directly to a 9.19-m trawl (3) with and (4) without a horizontal wire and plastic streamers. Despite more surface area (7.5 vs 6.0 m$^2$), both beam-trawl configurations had significantly lower drag than the otter trawls (≤30%). When catches were standardised to per ha, the otter trawl with sweeps retained significantly more (1.3–2.4 times) school prawns, *Metapenaeus macleayi* (Haswell), than the other three configurations. Within systems, removing sweeps or adding a horizontal wire significantly reduced the unwanted catches of a key teleost (southern herring, *Herklotsichthys castelnaui* Ogilby) by 41 and 48%. The results illustrate the utility of simple anterior modifications for independently addressing penaeid-trawling environmental issues.

KEYWORDS: beam trawls, bycatch reduction, drag, modifications, otter trawls, penaeids.

## Introduction

Mobile demersal fishing gears, including beam and otter trawls, are among the most commonly used commercial methods, accounting for approximately 25% of the total global catch or approximately 15% of all marine fish and >80% of shrimp/prawn catches (Kelleher 2005; Watson *et al.* 2006). While their contribution towards global harvests is important, demersal trawls, and especially those targeting penaeids, often are associated with poor size and species selectivity (Kelleher 2005) and indirect (e.g. predator removal) effects on epifauna and infauna (Kaiser *et al.* 2002). Such impacts cause varying levels of unaccounted fishing mortality and can have negative consequences for key stocks and habitats (Broadhurst *et al.* 2006). Demersal trawling also requires large amounts of fuel, often representing up to 30% of an operator's total costs (Thomas *et al.* 2010).

Historical recognition of the above ecological and economic issues has led to the investigation of resolution strategies mostly via isolated attempts at improving size and species selection using retrospectively fitted bycatch reduction devices in penaeid (e.g. Broadhurst 2000) and fish trawls (e.g. Jennings & Revill 2007) and proposing

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alternatives that reduce benthic impacts (Kaiser *et al.* 2002; Kennelly & Broadhurst 2002). Recently, improved fuel efficiencies have been achieved through better vessel engineering (e.g. hull design or propulsion systems; Thomas *et al.* 2010), trawl designs and operation (i.e. reduced towing and steaming speeds) (Parente *et al.* 2008). Although clearly validated improvements, many of these modifications require large capital investment and have rarely been implemented without legislation (Jennings & Revill 2007).

It is well established that to develop and introduce new fishing techniques to improve sustainability, there is a need to incorporate the fishers' perspective in the subsequent design and/or testing (Kennelly & Broadhurst 2002). Fishers are more likely to use new techniques if they perceive realised benefits, and there is limited capital investment (Jennings & Revill 2007). Applying cheap methods to improve sustainability is especially pertinent for small-scale/artisanal fisheries like penaeid otter trawling because they are associated with the greatest bycatch rates (Kelleher 2005). One possible alternative for improving species selection in some such fisheries is to simply substitute the otter boards for a lightweight beam; the presence of which can produce sufficient stimuli to direct some swimming fish away from the mouth of the trawl (Broadhurst *et al.* 2012). Equally important, a beam should also reduce both drag and seabed-habitat impacts – owing to relatively less contact by the parallel sleds (Broadhurst *et al.* 2012).

However, one potential issue for fishers associated with removing otter boards from penaeid trawl systems is that any reduction in substrate penetration (and therefore total-system contact) could result in fewer penaeids being dislodged and herded into the trawl (e.g. Broadhurst *et al.* 2012, 2014). It may be possible to address this issue by increasing the trawl footrope length, which can be justified from an environmental point of view because it is generally accepted that otter boards inflict relatively more habitat damage (Gilkinson *et al.* 1998). It is also possible that despite some increase in footrope length and including a beam and two sleds, the system could still have relatively lower drag than using a smaller trawl with otter boards (as otter boards can contribute up to 40% of the total drag of some configurations; Sterling 2000), although the boundaries of such a relationship remain unknown.

Irrespective of the spreading mechanism, it may also be possible to improve the size and especially species selectivity of penaeid trawls via simple modifications within existing configurations. For example, because it is well established that sweep wires (between the spreading mechanism and the trawl; Figure 1a) can herd fish inwards (e.g. Engås & Godø 1989; Andrew *et al.* 1991) their removal could reduce catches. Additionally, like a rigid beam, and as suggested by Broadhurst *et al.* (2012), horizontal vibrating wires and/or obstructions across the mouth of the trawl might herd fish away; either via visual or tactile responses (e.g. Main & Sangster 1983). Fish are known to respond to both visual and auditory stimuli (Ladich & Fay 2012), but there is a paucity of research exploiting such behaviour to promote their avoidance of penaeid trawls. Such research is important, since intuitively, modifications that facilitate avoidance are likely to be associated with lower unaccounted fishing mortality than those that promote escape from the codend (Broadhurst *et al.* 2006).

Considering the above, the aims of this study were to investigate the potential for simple within-system and between-system modifications for improving the ecological efficiency of small penaeid trawls. Specifically, the study aimed to compare (1) the relative catching and engineering performances of trawls spread by either otter boards or a beam and concurrently (2) the effectiveness of the presence or absence of sweep wires for the otter trawl and a novel modification involving a horizontal wire across the mouth of the beam trawl. To standardise total system contacts more closely (i.e. accounting for the loss of substrate penetration by the otter boards), the footrope lengths of the beam trawls were increased. The work was done in Australia, but the results have broader implications among national and international small-scale penaeid-trawl fisheries.

## Material and methods

### *Fishing vessel, monitoring equipment and tested treatments*

The experiment was completed in the Lake Wooloweyah estuary (29° 26′S 153° 22′E; sand and mud substrata approximately 1–2 m depth) during summer 2013 using a 10-m double-rigged trawler (104-kw). The trawler had 40-m bridles (6-mm-diameter Ø stainless steel wire) on a two-drum hydraulic winch and was equipped with: a global positioning system (GPS; Lowrance, HDS5) to record speed over the ground (SOG in $ms^{-1}$); fuel monitor (Floscan series 9000); sum log (model: Bronze + Log) to record speed through the water (STW in $ms^{-1}$); and attachable load cells (Amalgamated Instrument Company; model no. PA6139) to measure the combined tension (kgf) in the paired bridles, which were always deployed to 12 m where required (see below) replicate measures of the wing-end spreads of relevant trawls were obtained using Notus paired wireless sensors. The data from the sensors were received through an omnidirectional hydrophone and logged onto a laptop. All electronic data were recorded every 60 s.

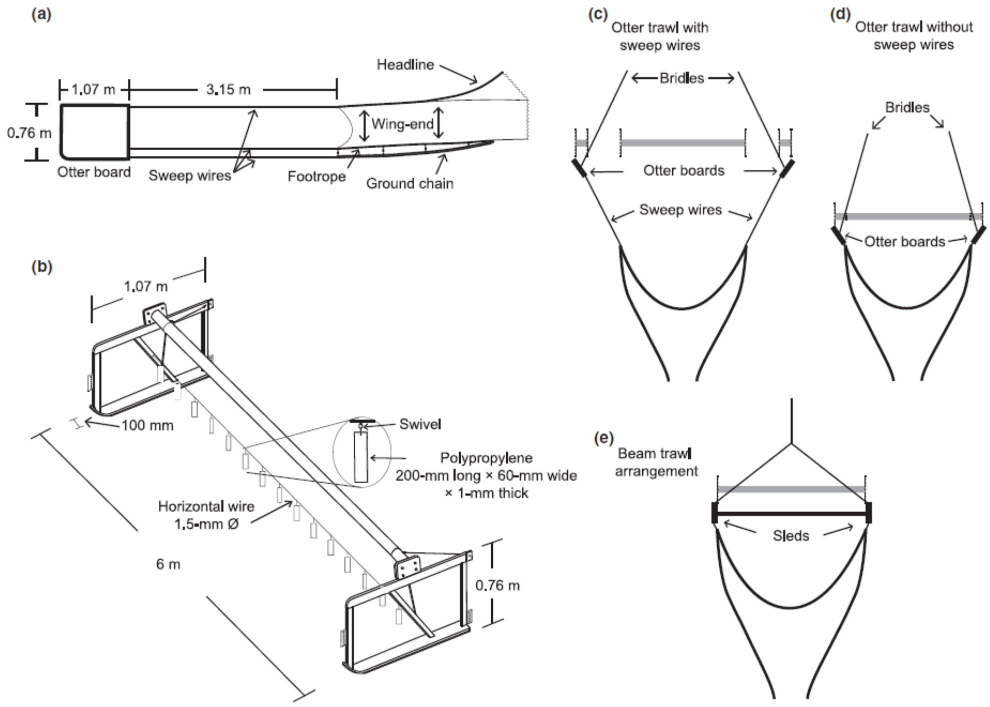


**Figure 1.** Schematic representation of (a) an otter-board and wing-end section, (b) the beam with a highlighted view of an individual strip of a polypropylene, and (c–e) each spreading-mechanism configuration during deployment. The shaded areas between the parallel dashed lines represent total-system contacts.

Two identical beam assemblies (each 108 kg) were built; each comprising an aluminium yacht mast (6.00 m long × 0.14 m wide × 0.08 m deep) and galvanised-steel sleds (1.07 m long × 0.76 m high × 0.10 m base plates; Figure 1b). The beam length was based on the maximum considered operationally practical by the fisher. Two pairs of cambered, stainless steel otter boards (each 1.07 m long × 0.76 m high × 54 kg in air total weight) were also constructed. A beam configuration and pair of otter boards were assigned to one side of the trawler throughout the experiment.

Four trawl bodies – two each of 7.35-m (labelled A and B) and 9.19-m (C and D) headline and footrope lengths – were constructed from the same nominal 42-mm (stretched mesh opening – SMO) mesh (identical 1.25-mm Ø twisted polyethylene (PE) twine) for use with the paired otter boards and each beam, respectively (Figure 2). All trawls had a posterior circumference of 150 transversals (T) (50 T for the top and bottom panels and 25 T for each side panels; Figure 2). The headline length of the beam trawl was calculated based on a hypothesised spread ratio (proportion of wing-end spread to headline length) of 0.65 for the otter trawl – derived from a model proposed by Sterling (2000). All trawl bodies were rigged with identical Nordmøre-grids (28-mm bar spacing) in extension sections comprising nominal 40-mm PE mesh (2.50-mm Ø twisted twine) and square-mesh codends made from nominal 27-mm polyamide mesh (1.25-mm Ø twine) hung on the bar (see Broadhurst *et al.* 2012 for specifications). The twine areas were 4.80 and 6.38 $m^2$ for each trawl (comprising body, extension and codend) attached to the otter boards and beam, respectively. Total-system areas were calculated as the sum of the twine, ground-chain, sweep wires (if present), frame lines, catch (0.23 $m^2$) and either the otter boards (× 2) or the beam-and-sled areas and were 6.99 and 7.48 $m^2$ for each otter- and beam-trawl configuration.

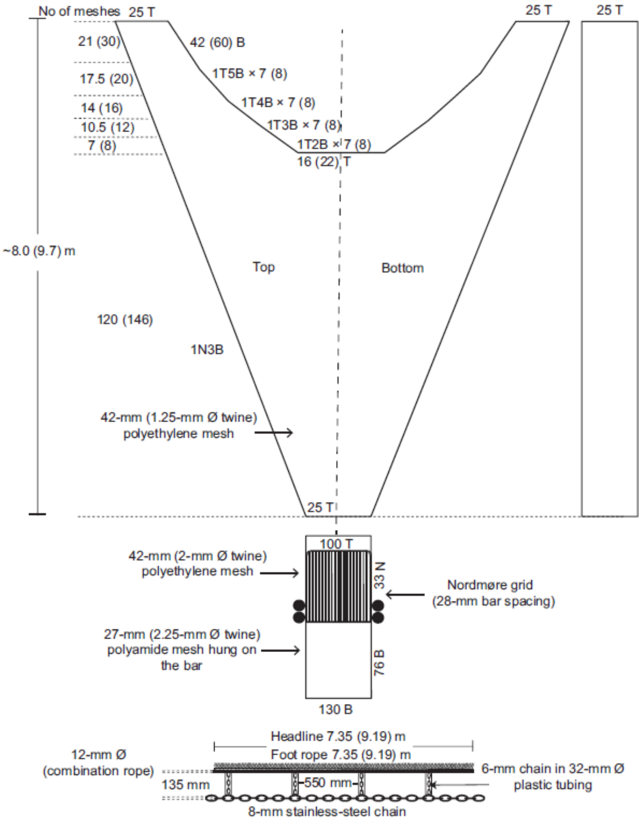


**Figure 2.** Plans of the 7.35- (labelled A and B) and 9.19-m (C and D; inside parentheses) trawl bodies used in the experiment. T, transversals; B, bars; N, normals; and ∅, diameter.

### *Experimental design*

Prior to starting the work, the four trawl bodies, extensions and codends were checked for mesh uniformity by measuring 15 replicate SMOs using a local, purpose-built gauge. In total, four treatments (two within each spreading mechanism) were deployed in four-day blocks (with replicate 40-min deployments for each treatment) over 12 days. The treatments included the otter trawls (1) with and (2) without three sweep wires (each 6-mm Ø stainless steel wire and 3.15 m long between each otter board and wing-end; Figure 1a, c and d) and the beam trawls (3) with and (4) without a horizontally strung 1.50-mm Ø stainless steel wire. It was hypothesised that adding the horizontal wire would evoke an escape response among fish and removing the sweep wires would herd fewer fish into the net (Figure 1b–e). The horizontal wire was attached to the centre of the sleds 0.35 m below the 6-m beam and in front of the trawls (Figure 1b). Flat strips of green polypropylene (200 mm long × 60 mm wide × 1 mm thick) were secured to the wire (0.40 m apart) using swivels (Figure 1b).

On each day, one of the above four spreading-mechanism treatments was assigned to a side of the vessel where it remained. One of the two designated trawls within each spreading mechanism was then attached and deployed either three times (on the beam), or two or four times (on the otter boards) after which trawls (within-spreading mechanisms) were swapped. The pairs of the Notus sensors were randomly assigned to the A and B otter trawls for two consecutive deployments, before being swapped. Throughout the experiment, each pair of Notus sensors was used 36 times (18 times on each trawl). Load cells were assigned to each Notus-sensor pair and followed their sampling order on the otter trawls and were similarly rotated among the beam-trawl deployments.

At the end of each deployment, the two codends were simultaneously emptied onto a partitioned tray and the catches separated, with the total weights of penaeids and bycatch recorded along with the numbers or weights (see below) of each bycatch species for each trawl. Total lengths (TL to the nearest 5 mm) of the most abundant teleosts were also recorded. A random sample of approximately 500 g of penaeids was collected and then separated by species in the laboratory. Numbers and weights were recorded and approximately 100 individuals of the most abundant species (school prawns, *Metapenaeus macleayi* (Haswell) – see Results) were measured for their carapace lengths (CL to the nearest 1 mm). These data were used to estimate the totals (numbers and weights) of each penaeid species in each deployment for *M. macleayi*. In addition to the living bycatch, all debris were recorded by weight.

### *Data analyses*

To confirm trawl homogeneity, the hypothesis of no differences in the SMOs of the various bodies, extensions and codends was tested in a linear model (LM). The remaining biological and technical data collected during fishing were analysed to test the general assumption of no differences among the four spreading-mechanism treatments, but in different formats. For each deployment, the numbers and weights of catches were treated in their unstandardised form (i.e. per 40-min deployment), and also after being standardised to per ha trawled using the area of footrope contact (i.e. average wing-end spread × the distance trawled).

Additionally, in an attempt to explain variability among the numbers and weights of *M. macleayi* between the beam and otter trawls (see Results), the latter data were also standardised to the total-system contact area [(i.e. average wing-end spread + span of otter-board contact) × the distance trawled], where the span of each otter-board contact was calculated by multiplying the otter-board length (1.07 m) by the sine of the angle of attack (AOA; calculated from the predicted wing-end spread of each configuration and using the model proposed by Sterling (2000). This is a deterministic model of trawl performance that will always produce the same output from a given starting condition. Because the sweep wires were above the substratum, they were not included in total-system contact (Figure 1a). Similarly, the relatively thin (0.10 m) sled-base plates of the beams were outside the wing-ends and parallel to the tow direction, and so for these configurations the footrope and total-system contacts were considered synonymous (Figure 1e).

All (1) unstandardised and standardised catch data using the (2) footrope and (3) total-system contacts of the various configurations were then log-transformed to account for an assumed multiplicative relationship with causal factors and analysed in separate linear mixed models (LMMs), with the fixed effect of spreading-mechanism configuration and appropriate random factors (days, trawls, deployments × days, and sides of the vessel). Other biological data, including the mean CL of *M. macleayi* and replicate drag per deployment were analysed untransformed. Engineering data, including the area trawled, wing-end spread for the otter trawls, spread ratio and drag, were also analysed untransformed, and with appropriate covariates, including SOG and STW, and a variable termed *current* created by the difference between the two. The models were fitted using the lmer function from the lme4 package in R 2.15.3 (The R Project for Statistical Computing; http://www.r-project.org/) and the significance of trawl configuration determined using a likelihood ratio test (LRT). Any significant differences detected for spreading-mechanism configuration were subsequently explored using pair-wise comparisons in conjunction with the Benjamini–Hochberg–Yekutieli procedure to control the false-discovery rate (FDR; Benjamini & Yekutieli 2001).

Predicted means from the LMMs for drag were used to calculate relative fuel consumption associated with towing the four treatments. Specifically, assuming that for any given towing speed, the concomitant fuel usage was proportional to the drag, it is possible to determine the relative fuel consumption rate. Fuel consumption was standardised to per ha trawled and per kg of *M. macleayi* caught for each trawl design by comparing the predicted fuel consumption rate with predicted mean wing-end spread (the rate at which area was being swept for a given trawl speed), and the predicted mean absolute (per 40-min deployment) *M. macleayi* catches from the respective LMMs.

## Results

Thirty-six deployments of each spreading-mechanism configuration were completed over 12 days, catching approximately 519 and 132 kg of penaeids (nearly all were *M. macleayi*) and fish bycatch, respectively (Table 1). The bycatch comprised 40 species, although more than 89% of the total included southern herring, *Herklotsichthys castelnaui* (Ogilby) (5.0–18.5 cm TL;

**Table 1.** Scientific and common names and numbers (except blue blubber jellyfish – weights in kg only) of organisms caught during the experiment

| Family | Scientific name | Common name | Total |
|---|---|---|---|
| *Cnidarians* | | | |
| Catostylidae | *Catostylus mosaicus* | Blue blubber jellyfish | 78 |
| *Crustaceans* | | | |
| Palaemonidae | *Macrobrachium novaehollandiae* | Freshwater prawn | 37 |
| Penaeidae | *Metapenaeus macleayi* | School prawns* | 223 722 |
| | *Metapenaeus bennettae* | Green tail prawn* | 267 |
| | *Penaeus monodon* | Tiger prawn* | 39 |
| | *Peneaus plebejus* | Eastern king prawn* | 1102 |
| Portunidae | *Portunus armatus* | Blue swimmer crab* | 19 |
| | *Scylla serrata* | Giant mud crab* | 2 |
| *Elasmobranchs* | | | |
| Dasyatididae | *Dasyatis* sp | Stingray | 44 |
| *Molluscs* | | | |
| Loliginidae | *Uroteuthis* sp | Squid | 253 |
| *Teleosts* | | | |
| Ambassidae | *Ambassis jacksoniensis* | Port Jackson glassfish | 128 |
| | *Ambassis marianus* | Ramsey's perchlet | 859 |
| Antennariidae | *Antennarius striatus* | Striate anglerfish | 1 |
| Apogonidae | *Siphamia roseigaster* | Pink-breasted siphonfish | 124 |
| Ariidae | *Arius graeffei* | Forktail catfish* | 74 |
| Carangidae | *Caranx sexfasciatus* | Bigeye trevally* | 6 |
| Clupeidae | *Herklotsichthys castelnaui* | Southern herring* | 4460 |
| | *Hyperlophus vittatus* | Whitebait* | 46 |
| Eleotridae | *Gobiomorphus australis* | Striped gudgeon | 4 |
| Engraulidae | *Engraulis australis* | Australian anchovy | 470 |
| Gerreidae | *Gerres subfasciatus* | Silver biddy* | 660 |
| Gobiidae | *Arenigobius bifrenatus* | Bridled goby | 10 |
| Hemiramphidae | *Arrhamphus sclerolepis* | Snubnose garfish* | 1 |
| | *Hyporhamphus regularis* | River garfish* | 12 |
| Monacanthidae | *Aluterus monoceros* | Unicorn leatherjacket | 1 |
| Monodactylidae | *Monodactylus argenteus* | Diamond fish | 19 |
| Mugilidae | *Liza argentea* | Flat-tail mullet* | 26 |
| | *Mugil cephalus* | Bully mullet* | 197 |
| Muraenesocidae | *Muraenesox bagio* | Common pike eel | 1 |
| Paralichthyidae | *Pseudorhombus arsius* | Largetooth flounder* | 12 |
| Platycephalidae | *Platycephalus fuscus* | Dusky flathead* | 5 |
| Plotosidae | *Euristhmus lepturus* | Long-tailed catfish* | 86 |
| Pomatomidae | *Pomatomus saltatrix* | Tailor* | 971 |
| Priacanthidae | *Priacanthus macracanthus* | Red bigeye | 2 |
| Sciaenidae | *Argyrosomus japonicas* | Mulloway* | 2 |
| Sillaginidae | *Sillago ciliata* | Sand whiting* | 7 |
| Soleidae | *Synclidopus macleayanus* | Narrow banded sole | 13 |
| Sparidae | *Acanthopagrus australis* | Yellowfin bream* | 1184 |
| | *Rhabdosargus sarba* | Tarwhine* | 31 |
| Terapontidae | *Pelates quadrilineatus* | Trumpeter* | 29 |
| Tetraodontidae | *Tetractenos glaber* | Toadfish | 147 |
| Tetrarogidae | *Notesthes robusta* | Bullrout | 8 |

* Economically important.

46.3%), yellowfin bream, *Acanthopagrus australis* (Owen) (4.0–24.5 cm TL; 12.3%), tailor, *Pomatomus saltatrix* (L) (2.5–15.0 cm TL; 10.1%), Ramsey's perchlet, *Ambassis marianus* (Günther) (3.0–11.0 cm TL; 8.9%), silver biddy, *Gerres subfasciatus* (Cuvier) (3.0–14.5 cm TL; 6.8%) and Australian anchovy, *Engraulis* *australis* (White) (3.0–9.0 cm TL; 4.9%) (Table 1). Blue blubber jellyfish, *Catostylus mosaicus* (Quoy & Gaimard) was also common (Table 1), while debris were restricted to empty shells of *Anadara trapezia* (Deshayes) and *Spisula trigonella* (Lamarck) (approximately 101 kg total). Analyses of catch data were limited to the variables above, and only those of interest were graphed.

In addition to shells, the wing-end meshes of the trawls without sweep wires accumulated more sediment than the other three configurations. These clogged meshes formed an approximate right-angle triangle with a base extending approximately 2.5 m along the footrope.

### Engineering performances

The SMOs were not significantly different between trawls, extensions or codends, with overall means ± SE of 41.25 ± 0.08, 41.40 ± 0.17 and 27.35 ± 0.10 mm, respectively (LM, $P > 0.05$). There was a significant effect of spreading-mechanism configuration on wing-end spread that manifested as a significantly greater spread ratio (SR) for the otter trawl without sweep wires (0.71 ± 0.01; or a predicted mean of 5.25 ± 0.04 m) than with sweep wires (0.67 ± 0.01 or 4.96 ± 0.04 m) and, irrespective of sweep wires, both otter-trawl configurations were spread at significantly greater ratios than the beam trawl (both 0.65 ± 0.00 or 6.00 ± 0.00 m, LMM and FDR, $P < 0.05$; Tables 2–4). Within the otter-board configurations, the absence of sweep wires increased the AOA by 3° (Tables 3).

Drag was also significantly affected by spreading-mechanism configuration, although in addition to the random variables assessed above for wing-end spread, the parsimonious model also included SOG, which presented as a positive relationship irrespective of configuration (LMM, $P < 0.001$, Table 2). Predicted mean drags for spreading-mechanism configuration are presented at the centred value of SOG ($ms^{-1}$) that were derived from the range of logged data for the otter trawl with (0.93–1.95 $ms^{-1}$) and without sweep wires (0.77–1.95 $ms^{-1}$) and the beam trawl with (0.93–1.95 $ms^{-1}$) and without (0.77–1.80 $ms^{-1}$) a horizontal wire. Compared with both otter-trawl configurations, the beam trawls had significantly lower drags (predicted means reduced by 27–31%; FDR, $P < 0.001$; Tables 3 and 4). In terms of fuel, this equated to approximately 2.8 and approximately 2.2 L $ha^{-1}$ for footrope and total-system contacts, respectively, for both otter-trawl configurations, with the beam trawls using approximately 1.8 L $ha^{-1}$ for footrope/total-system contacts (Table 3).

**Table 2.** Summaries of likelihood ratio test (LRT) statistics from linear mixed models assessing the importance of the fixed effect of spreading-mechanism configuration (otter trawls with and without sweep wires, and beam trawls with and without a horizontal wire) in explaining variability among engineering and biological variables.

| | LRT |
|---|---|
| Engineering variables | |
| Wing-end spread | 38.01*** |
| Drag | 20.78*** |
| Biological variables | |
| Wt of *M. macleayi* 40 $min^{-1}$ | 20.24*** |
| Wt of *M. macleayi* $ha^{-1}$ of footrope contact | 23.95*** |
| Wt of *M. macleayi* $ha^{-1}$ of total-system contact | 20.76*** |
| No. of *M. macleayi* 40 $min^{-1}$ | 21.14*** |
| No. of *M. macleayi* $ha^{-1}$ of footrope contact | 24.49*** |
| No. of *M. macleayi* $ha^{-1}$ of total-system contact | 24.11*** |
| Mean CL of *M. macleayi* | 8.36* |
| Wt of *Catostylus mosaicus* 40 $min^{-1}$ | 10.67* |
| Wt of *Catostylus mosaicus* $ha^{-1}$of footrope contact | 5.92 |
| Wt of empty shells 40 $min^{-1}$ | 88.29*** |
| Wt of empty shells $ha^{-1}$ of footrope contact | 89.36*** |
| Wt of fish bycatch 40 $min^{-1}$ | 16.79*** |
| Wt of fish bycatch $ha^{-1}$ of footrope contact | 21.14*** |
| No. of fish bycatch 40 $min^{-1}$ | 13.13** |
| No. of fish bycatch $ha^{-1}$ of footrope contact | 17.32*** |
| No. of *Herklotsichthys castelnaui* 40 $min^{-1}$ | 22.30*** |
| No. of *Herklotsichthys castelnaui* $ha^{-1}$ of footrope contact | 24.72*** |
| No. of *Acanthopagrus australis* 40 $min^{-1}$ | 3.86 |
| No. of *Acanthopagrus australis* $ha^{-1}$ of footrope contact | 4.83 |
| No. of *Pomatomus saltatrix* 40 $min^{-1}$ | 4.61 |
| No. of *Pomatomus saltatrix* $ha^{1}$ of footrope contact | 3.19 |
| No. of *Ambassis marianus* 40 $min^{-1}$ | 1.31 |
| No. of *Ambassis marianus* $ha^{-1}$ of footrope contact | 1.68 |
| No. of *Gerres subfasciatus* 40 $min^{-1}$ | 1.73 |
| No. of *Gerres subfasciatus* $ha^{-1}$of footrope contact | 3.07 |
| No. of *Engraulis australis* 40 $min^{-1}$ | 2.16 |
| No. of *Engraulis australis* $ha^{-1}$ of footrope contact | 1.29 |

Numbers and weights were analysed per 40-min deployment and standardised to per ha trawled calculated using the footrope contact (average wing-end spread × distance trawled) and, additionally for *Metapenaeus macleayi*, the total-system contact [(i.e. wing-end spread + span of otter-board contact) × the distance trawled] and then log-transformed.
* $P < 0.05$
** $P < 0.01$
*** $P < 0.001$

### Catching performances

Spreading-mechanism configuration significantly affected the catches of *M. macleayi* and their sizes, fish bycatch, *H. castelnaui* and empty shells across all categories (i.e. per 40-min deployment and ha trawled) and the weight of *C. mosaicus* per 40-min deployment (LMM, $P < 0.05$; Tables 2 and 4, Figures 3a and b and 4a–d). Subsequent FDR pair-wise comparisons revealed that in

**Table 3.** Summary of predicted mean ± SE wing-end spreads (m), spread ratios, drags (kgf), and other mean performance indicators for the four spreading-mechanism configurations

| | Otter trawl with sweep wires | Otter trawl without sweep wires | Beam trawl without a horizontal wire | Beam trawl with a horizontal wire |
|---|---|---|---|---|
| Otter-board angle of attack (°) | 36 | 39 | na | na |
| Wing-end spread (m) | 4.96 (0.04)$^A$ | 5.25 (0.04)$^B$ | 6.00 (0.00)$^C$ | 6.00 (0.00)$^C$ |
| Spread ratio | 0.67 (0.01) | 0.71 (0.01) | 0.65 (0.00) | 0.65 (0.00) |
| Drag (kgf) | 142.59 (30.71)$^A$ | 148.26 (30.66)$^A$ | 102.18 (26.58)$^B$ | 103.56 (30.73)$^B$ |
| Fuel rate (L $h^{-1}$) | 6.738 | 7.075 | 5.224 | 5.294 |
| Fuel intensity | | | | |
| L $ha^{-1}$ (FRC) | 2.808 | 2.808 | 1.804 | 1.810 |
| L $ha^{-1}$ (TSC) | 2.235 | 2.235 | 1.804 | 1.810 |
| L $kg^{-1}$ | 0.990 | 1.237 | 1.008 | 1.320 |

Litres of fuel per ha were calculated using both the footrope (FRC–average wing-end spread × distance trawled) and total-system contacts (TSC–average wing-end spread + otter-board span on the bottom) × distance trawled). Mean predicted drags were derived with a centred value of SOG and with zero current. Dissimilar superscript letters indicate significant differences detected in false-discovery-rate pair-wise comparisons ($P < 0.001$).

**Table 4.** Summary of the acceptance (A) or rejection (R) of the null hypothesis (of no difference in the relative performance) for key response variables among the various pair-wise comparisons of the four treatments of interest; (1) otter trawl with sweep wires (O with W), (2) otter trawl without sweep wires (O without W), (3) beam trawl with a horizontal wire (B with W), and (4) beam trawl without a horizontal wire (B without W)

| Ho = no Pair-wise comparison | Prawns | Bycatch | Drag |
|---|---|---|---|
| O with W vs O without W | A | R | A |
| O with W vs B without W | R | R | R |
| O with W vs B with W | R | R | R |
| O without W vs B without W | R | A | R |
| O without W vs B with W | R | A | R |
| B with W vs B without W | R | A | A |

terms of catches per 40-min deployment, both otter-trawl configurations caught the same quantities of *M. macleayi* ($P > 0.05$) but significantly more (predicted mean increases of up to double) than the beam trawl configurations ($P < 0.05$; Figure 3a and b). Further, within beam-trawl configurations, the presence of the horizontal wire was associated with a significant reduction in catches of *M. macleayi* (by 21%; FDRs, $P < 0.05$; Figure 3a and b). These differences were maintained for standardised catches, except that the otter trawl with sweep wires caught significantly more *M. macleayi* than without for both footrope and total-system contacts (by up to 29%; FDRs, $P < 0.05$; Figure 3a and b). In terms of *M. macleayi* sizes, the beam trawl with the horizontal wire caught significantly larger CLs (by up to 0.5 mm) than the otter trawl without sweep wires (FDR, $P < 0.05$), but there were no other pair-wise differences (FDRs, $P > 0.05$; Figure 4). Both the otter trawl with sweep wires and the beam trawl without the horizontal wire had similar fuel intensities for *M. macleayi* (at approximately 1.0 L $kg^{-1}$), while the otter trawl without sweep wires and the beam trawl with the horizontal wire operated at 1.2 and 1.3 L $kg^{-1}$, respectively (Table 3).

The FDR pair-wise comparisons for fish bycatch showed that the otter trawl with sweep wires caught a significantly greater weight (1.6–2.0 times) per 40-min deployment, and number (up to 2.0 times) and weight (up to 2.4 times) per ha of footrope contact, than the other three spreading-mechanism configurations ($P < 0.01$; Figure 5a and c). By comparison, for the number of fish bycatch per 40-min deployment, the otter trawl with sweep wires similarly caught significantly more (by up to 1.6 times) than the otter trawl without sweep wires and the beam trawl with the horizontal wire (FDR, $P < 0.01$), but not the beam trawl without the horizontal wire (FDR, $P > 0.05$; Figure 5c).

For the most abundant fish species, *H. castelnaui*, the beam trawl with the horizontal wire retained significantly fewer per 40-min deployment (predicted means reduced by 47–69%) and per ha of footrope contact than all other spreading-mechanism configurations (by 49–75%, FDR, $P < 0.01$; Figure 5d). The predicted mean numbers of other abundant fish, including *P. saltatrix* and *A. australis*, were not significantly different among spreading-mechanism configurations (LMM, $P > 0.05$; Figure 5e and f). By comparison, both beam-trawl configurations retained significantly greater weights (1.7 times) of *C. mosaicus* per 40-min deployment than the otter trawls (FDR, $P < 0.01$), but no significant differences were detected for standardised catches (FDR, $P > 0.05$; Fig-

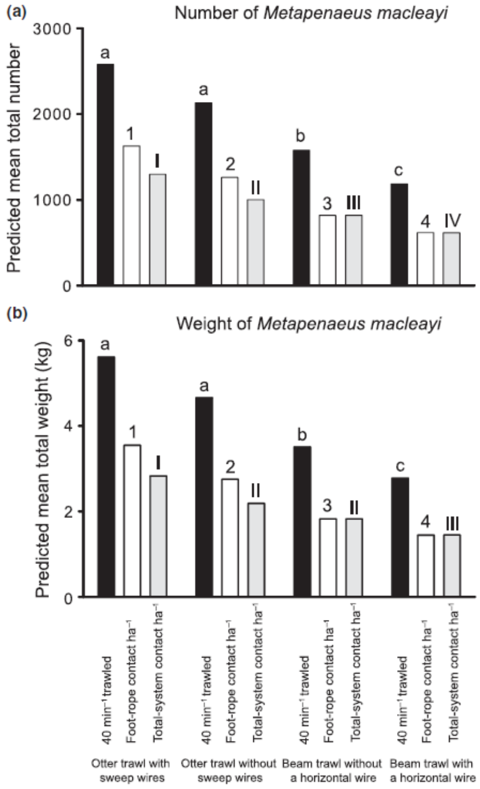


**Figure 3.** Differences between the four spreading-mechanism configurations for predicted mean (a) numbers and (b) weights of school prawns, *Metapenaeus macleayi* per 40-min deployment and standardised to per ha trawled using the footrope (average wing-end spread × distance trawled) and the total-system contacts [(wing-end spread + pan of otter-board contact) × the distance trawled]. Dissimilar, letters, numbers and roman numerals above the histograms indicate significant differences detected in false-discovery-rate pair-wise comparisons ($P < 0.05$).

ure 5b). The otter trawl without sweep wires retained significantly more shells (99%) than the other three configurations for both per 40-min deployment and standardised catches (FDR, $P < 0.001$).

## Discussion

The results from this study reiterate the utility of modifying penaeid trawl anterior sections for improving their ecological efficiencies; measured here as reductions in bycatch and drag and therefore the fuel rate and intensity

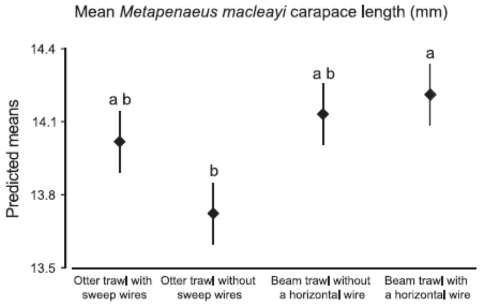


**Figure 4.** Predicted mean (±SE) carapace lengths for school prawns, *Metapenaeus macleayi* per 40-min deployment for the four spreading-mechanism configurations. Dissimilar letters above the histograms indicate significant differences detected in false-discovery-rate pair-wise comparisons ($P < 0.05$).

(Sumpton *et al.* 1989; Broadhurst *et al.* 2012, 2014; Table 4). The observed differences between between-spreading-mechanism and within-spreading-mechanism configurations can be discussed according to the key underlying engineering changes and possible species-specific responses, and ultimately used to provide directions for ongoing research.

There were between-system drag differences that highlight the important contribution of the otter boards to the relevant cumulative total drag. Specifically, despite their 25% longer headline lengths (and associated 33% greater twine area) and not withstanding slight differences in spread ratio (see below), the beam trawls had significantly lower drags (up to 31%, corresponding to approximately 1.9 L less fuel per h) than the otter trawls. By considering the tension in the towing warp and the sweep wires (calculated from netting drag), the total hydrodynamic forces and the ground shear, it is possible to estimate the contribution of the otter boards towards total-system drag at approximately 45% (Sterling 2000). Understanding the extent of such a contribution is important, being irrespective of between-system changes, simple alterations to the design (e.g. foil shape and aspect ratio) or configuration (e.g. AOA) of existing otter boards could improve trawl efficiency.

While more detailed investigations of otter-board performance in response to rigging arrangements/configurations are required, it is evident that simply removing the sweep wires significantly increased wing-end spread and with some (albeit non-significant) increase in drag (the predicted mean was 6 kg greater). This result can be attributed to a slight reduction in bridle angle caused by a narrower total gear span as the sweeps were removed. The lower bridle angle meant that less overall spreading

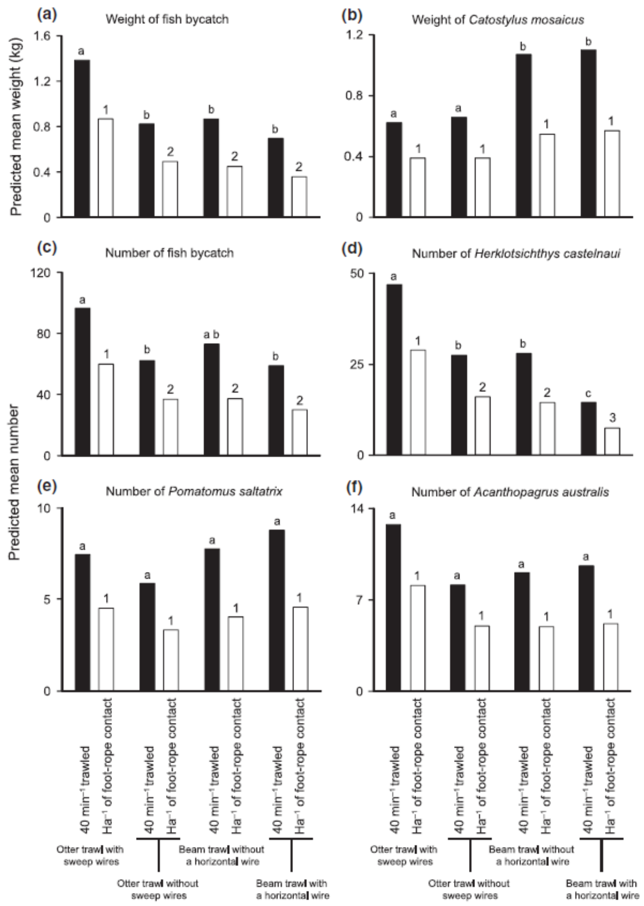


**Figure 5.** Differences in predicted mean weights of (a) fish bycatch and (b) blue blubber jellyfish, *Catostylus mosaicus*, and the numbers of (c) fish bycatch, (d) southern herring, *Herklotsichthys castelnaui*, (e) tailor, *Pomatomus saltatrix*, and (f) yellowfin bream, *Acanthopagrus australis* per 40-min deployment and standardised to per ha trawled using the footrope contact (average wing-end spread × distance trawled) for the four spreading-mechanism configurations. Dissimilar letters and numbers above the histograms indicate significant differences detected in false-discovery-rate pairwise comparisons ($P < 0.05$).

force from the otter boards was required, with the surplus simply increasing SR.

Irrespective of the sweeps, both otter-trawl configurations also had greater SRs than the beam trawls (i.e. predicted mean differences of 0.02 and 0.06). Such differences warrant consideration, not only in terms of engineering performances but also relative catching efficiencies. For example, Broadhurst *et al.* (2014) showed that compared with beam trawls rigged at a SR of 0.5, the same designs configured at between 0.6 and 0.8 caught significantly fewer *M. macleayi* and fish per trawled ha. One explanation for this result was that the corresponding steeper wing angles increased the probability of mesh encounters and escape for *M. macleayi* and were less efficient for herding fish (Broadhurst *et al.* 2014).

While the possibility for confounding effects of SR exists here, it was considered either unlikely or of minimal importance for two reasons. First, the maximum difference between SRs here was a lot lower than those tested by Broadhurst *et al.* (2014) (e.g. 9 vs 25–60%) and so the geometric consequences might also be minimal. Second, unlike the earlier study and independent of all other variables, positive correlations were observed between catches of both *M. macleayi* and *H. castelnaui* (the only teleost significantly impacted by any of the treatments) and SR. Assuming few confounding SR effects, the observed differences in catches can be attributed to the key treatment effects of interest: the spreading mechanisms and within-system changes.

For some variables, including the non-responsive shell debris and *C. mosaicus*, the direct consequences of the above within- and between-system engineering changes were evident in their absolute catches (per 40-min deployment). For example, removing the sweeps meant that shells disturbed by the otter boards were directed into the wings, instead of passing anteriorly, while the beam-trawl configurations caught more *C. mosaicus*, simply because of the longer headline. However, such simple trends were not apparent for the other key species – results that probably reflect behavioural responses to stimuli and therefore need to be discussed in terms of standardised catches (to remove the confounding effects of different swept areas).

With respect to *M. macleayi* behaviour, it is well established that most individuals reside in or on the substratum during the day (Ruello 1973). Other studies have shown that the typical response of such benthic-orientated penaeids to external stimuli is to contract their abdomen, which in the case of a contact with a footrope, propels them upwards and into the trawl mouth (Watson 1989). After subsequent contractions (and random propulsions) within the trawl, individuals were observed to attempt to orientate back into the substratum, but inevitably were directed by the panels of netting into the codend (Watson 1989).

Like the footrope, otter boards might be expected to disturb *M. macleayi* and potentially direct some towards the approaching trawl (Broadhurst *et al.* 2012, 2014). In this study, this hypothesis was tested by also standardising *M. macleayi* catches to total-system contact (which included the span of the otter-board base plates on the substratum), although the otter trawls still retained significantly more *M. macleayi* than the beam trawls. However, such a result could indicate that otter boards are more than 100% efficient for their span. For example, owing to their weight, otter boards penetrate the substratum more deeply than the footrope and are thus likely to disturb more buried organisms (Kaiser *et al.* 2002).

The potential behavioural response of *M. macleayi* to the otter boards might also explain why there was a significant reduction in catches and a bias towards smaller individuals in the absence of sweeps. Removing the sweep wires would reduce the opportunity for any *M. macleayi* disturbed by the otter boards to settle back into the substratum before being overtaken by the trawl. It is also possible that because the swimming ability of individuals might be proportional to their size (e.g. Daniel & Meyhofer 1989), some of the larger *M. macleayi* disturbed by the otter boards might have escaped over the headline, explaining the observed size differences.

Although speculative in the absence of *in situ* observations, the observed size bias and significant reduction in *M. macleayi* catches by the beam trawl with the horizontal wire might be explained by similar behaviour as above. The length and likely motion of the plastic strips meant that they could have disturbed the substratum anterior to the trawl mouth and in doing so, may have stimulated some *M. macleayi* before they encountered the ground gear, facilitating their escape.

Like for *M. macleayi*, species-specific behavioural responses could explain the observed differences in catches of *H. castelnaui* between- and within-spreading mechanisms. For example, previous studies have identified positive relationships between sweep length and fish catches, although the effects can be quite species-specific; potentially reflecting a range of variables, including swimming performances, and perhaps responses to visual or tactile stimuli (Engås & Godø 1989; Wardle 1989; Andrew *et al.* 1991). The results here support this trend with *H. castelnaui* the only species (of the six assessed) that significantly responded to the horizontal or sweep wires.

The differential, consistent response of *H. castelnaui* to the between- and within-system changes might reflect their extensive schooling behaviour. Other schooling species (e.g. gadoids and *Scomber scombrus*) have been observed to orientate equidistant between those components offering the greatest stimuli (e.g. the otter boards and sweep wires) with their subsequent retention in trawls influenced by their swimming capacity and endurance (Main & Sangster 1983). If the same stimuli affected *H. castelnaui*, then removing the sweep wires or adding a horizontal wire might be expected to negatively and positively affect the extent of reactions and therefore catches, depending on behavioural reactions in front of the trawl.

Trawling primarily relies on visual stimulus in the catching process, but fish reactions depend on a mixture of stimuli from the various trawl components (Main & Sangster 1983; Glass & Wardle 1989). For example, the colour and contrast of the gear will impact the visual senses while parts of the rigging (e.g. chains and shackles) will provide their own unique auditory signals, with tactile responses likely when visual stimuli are reduced or absent (Main & Sangster 1983; Glass & Wardle

1989). While the visual stimulus was standardised within treatments (e.g. the netting material and the spreading mechanisms within configurations were identical), the modifications would have disrupted consistency. Further research is required to more closely assess the stimuli evoking a response in *H. castelnaui* and also to elicit responses among other key species. Part of this work should include assessments of the utility of the above modifications at night (e.g. when many penaeid trawl fisheries operate) because visual cues will be reduced (Andrew *et al.* 1991; Walsh 1996).

Irrespective of the actual mechanisms contributing to the differences in catches, this study has important implications for ongoing work to improve the environmental efficiency of trawls. Specifically, choosing an appropriate sweep length (at least for penaeid trawls fished during the day) could represent a simple mechanism for improving species selectivity. Similarly, like for the beam trawl, it might be possible to extend a horizontal wire between otter boards. As part of this work, the hypotheses that any wires (either horizontal or sweep) provide auditory signals as they move through the water should be investigated.

With rising costs (e.g. fuel) and high unaccounted fishing mortality, applying appropriate modifications to penaeid trawls to improve fuel efficiencies and size and species selectivity has never been more pertinent. The results presented here illustrate the utility of within-system modifications to the anterior sections of penaeid trawls that are simple and require limited capital investment, but ultimately should contribute towards resolving the components of the above issues. Such characteristics support ongoing research.

## Acknowledgments

This study was funded by the New South Wales (NSW) Department of Primary Industries and the Australian Fisheries Research and Development Corporation (Grant no. 2011/010) in association with the University of Queensland. Thanks are extended to the (NSW) Professional Fishermen's Association, Greg Skilleter, Steve Everson, Don Johnson, Jen Marshall, Chris Barnes, Nick Sarapuk and especially Craig Brand.

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Fisheries Research 167 (2015) 180–189

Contents lists available at ScienceDirect

Fisheries Research

journal homepage: www.elsevier.com/locate/fishres

# Comparing three conventional penaeid-trawl otter boards and the new batwing design

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ARTICLE INFO

*Article history:*
Received 28 May 2014
Received in revised form 10 February 2015
Accepted 12 February 2015
Handling Editor A.E. Punt

*Keywords:*
Drag
Fuel reduction
Habitat impacts
Otter-board design
Penaeids

ABSTRACT

Three experiments were conducted to compare the engineering and catching performances of a hydrodynamic otter board termed the 'batwing' (comprising a sled-and-sail assembly, configured to operate at 20° angle of attack – AOA and with minimal bottom contact) against three conventional designs (termed the 'flat-rectangular', 'kilfoil' and 'cambered' otter boards) with AOAs between ~30 and 40°. Experiments involved paired penaeid trawls (7.35-m headlines). The first experiment compared the batwing otter boards against all other designs (using 41-mm mesh trawls). In experiment 2, the batwing was tested against the flat-rectangular design (with 32-mm mesh trawls). In experiment 3, the batwing and flat-rectangular otter boards were towed without trawls to facilitate estimates of their partitioned drag. Overall, compared to the conventional otter boards, the batwings had up to ~86 and ~18% less bottom contact and drag, respectively. Among the conventional otter boards, the trawls spread by the cambered design caught up to 13% more school prawns *Metapenaeus macleayi* attributed to their greater solid profile. No significant differences were detected among catches of fish in the trawls spread by the various otter boards. The results reaffirm that because otter boards contribute towards a large proportion of total system drag (estimated here at up to ~56%), their appropriate configuration is essential to maximise the fuel efficiency of penaeid-trawl systems.



## 1. Introduction

Penaeids are targeted throughout the world's tropical and temperate regions; mostly using small fishing vessels (<25 m) towing multi-net trawl systems that are laterally spread by paired hydro vanes, called 'otter boards' (Kelleher, 2005; Gillett, 2008). While there is considerable variety among otter-board designs, all encompass a substantial proportion of the entire trawling system weight to ensure sufficient seabed contact, and are orientated at an angle to the tow direction (termed the angle of attack – AOA). The water moving over otter boards creates hydrodynamic forces that horizontally open penaeid trawls to spread ratios (SR) typically 0.6–0.8 of their total headline length. The drag component of such hydrodynamic forces has been hypothesised to account for up to 30% of the total-system drag (Sterling, 2000).

At a broad level, the most common otter boards are simple flat, rectangular designs – although more hydrodynamically complex cambered variations are also popular (Seafish et al., 1993). Irrespective of design subtleties, the majority of otter boards are rigged to have AOAs between 30 and 40° (Seafish et al., 1993; Sterling, 2000). Operating conventional otter boards at such high AOAs helps to maintain their stability, which keeps the other trawl components at optimal efficiency (Patterson and Watts, 1985). Even slight reductions in AOA below this range can result in operational issues, manifesting as reduced stability and possibly lost effective fishing time (Patterson and Watts, 1985; Seafish et al., 1993). In an attempt to overcome such issues, a more recent prototype termed the 'batwing' otter board was developed by Sterling and Eayrs (2010) to remain at a constant 20° AOA, and with robust stability achieved through its unique rigging strategy (see Methods Section).

Although not extensively quantified (but see Patterson and Watts, 1985, 1986), compared to conventional designs, otter boards such as the batwing that have low AOAs should have relatively lower drag for the same spreading force and therefore require less fuel to tow. Calculating the extent of any such fuel reductions is complex. It is well established that the fuel consumed during trawling is proportional to the thrust applied by the trawler, if propeller efficiency remains constant (Prado, 1990). However, the

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http://dx.doi.org/10.1016/j.fishres.2015.02.013
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assumption of a proportional relationship between drag reductions and fuel savings remains approximate because many factors affect efficiency, including propeller loading.

Globally, it is becoming imperative to reduce fuel usage in many fisheries including demersal trawling, which has some of the greatest fuel-to-catch ratios, with fuel accounting for 30% of a trawl operator's total costs in developed countries (Suuronen et al., 2012). In fact, in Australia, trawlers use at least 55% of their fuel while trawling (with the rest used during travelling between trawl grounds and operating electrical equipment), and are operating close to their profitability threshold (Thomas et al., 2010; Wakeford, 2010).

Beyond drag/fuel savings, a potential concomitant benefit of lowering otter-board AOA is reduced benthic contact for any given length (i.e. ~1.5% for each degree the AOA is lowered), and subsequently fewer associated impacts. For example, an otter board ~1 m long deployed at 40° AOA will impact the bottom for ~64 cm, while at 20° its contact will be reduced to ~34 cm. Even slight reductions in impacts are potentially beneficial, considering that otter boards leave the most discernible track marks from trawl configurations (Caddy, 1973; Kaiser et al., 2002). However, from a catching perspective, one concern with minimising otter-board bottom contact is that a lower AOA could reduce substrate disturbance and negatively affect catches because penaeids mostly reside in the substratum (Broadhurst et al., 2012, 2013a; McHugh et al., 2014). Further, otter boards are known to herd fish (Wardle, 1989), either through visual or tactile stimuli, and so even subtle variations in their design and AOA might influence species selection by the trawl.

Despite the above, there have been very few formal studies of the effects of otter boards on the engineering and catching performances of penaeid trawls (but see Broadhurst et al., 2012, 2013b). The main aim of this study was to address this shortfall by quantifying the catches and fuel efficiency (measured as least drag) associated with three conventional otter-board designs and the batwing (with its relatively less bottom contact) in one Australian fishery targeting school prawns, *Metapenaeus macleayi*. A secondary aim was to use an approach involving removing the trawls and just towing the otter boards (separated by wire stays) to quantify their contribution towards total system drag for the tested trawls, so the benefits of future refinements to otter-board design and their AOAs can be established.

## 2. Methods

Three experiments were completed in the Clarence River, New South Wales, Australia, during May 2013 using a local penaeid trawler (10 m and 89-kw) fishing in ~4–18 m water-depth across mud and sand substratum. The trawler had 8-mm diameter (Ø) stainless warps and 40-m bridles (6-mm Ø stainless wire) on a double-drum, hydraulic, split winch. The trawler was also equipped with: a fuel monitor (Floscan series 9000); global positioning system (GPS; Lowrance); hull-mounted sum log (EchoPilot, Bronze Log+), warp-attachable load cells and associated data logger (Amalgamated Instrument Company; model nos PA6139 and TP4); and a portable acoustic, trawl-monitoring system with paired wing-end distance sensors (Notus Trawlmaster System; Model no. TM800ET; see Broadhurst et al., 2013a for details). All monitoring equipment was calibrated prior to starting the experiments.

### 2.1. Trawls and otter boards tested

Four trawls were constructed – two identical replicates of two similar designs (Fig. 1). The first two trawls (termed A and B) were conventionally mandated designs for the fishery, and comprised a mean stretched mesh opening (SMO) ± SE of 41.43 ± 0.11 mm ($n$ = 20 meshes in each trawl) and 1.2-mm Ø twine, with a side taper of 1N3B and were used in experiment 1 (Fig. 1). Owing to the small sizes of prawns encountered (see Results Section), the third and fourth trawls (labelled C and D) used in experiment 2 were made from smaller 31.61 ± 0.08 mm SMO ($n$ = 20 meshes in each trawl) and 0.8 mm Ø twine, and with a side taper of 1N5B (Fig. 1). All four trawls were rigged with identical Nordmøre-grids and square-mesh codends made from 27.37 ± 0.10-mm SMO ($n$ = 20 meshes in each trawl) polyamide mesh hung on the bar and had 2.89-m sweeps (6-mm Ø wire) attached at their wing ends, terminating in snap clips to facilitate attachment to the otter boards.

Four otter-board pairs were tested, all with 100 mm baseplates (Fig. 2). The first otter board represented a standard design used nationally and internationally, and comprised a mild-steel frame with marine-grade plywood inserts and was termed the 'flat-rectangular' (52.5 kg, 1.39 m × 0.61 m, solid area of 0.77 $m^2$; Fig. 2a). The second design ('kilfoil') was constructed entirely from galvanised mild steel and had three 270 mm-wide cambered vertical foils in a rectangular frame (63.0 kg, 1.25 m × 0.63 m, solid area of 0.58 $m^2$; Fig. 2b), while the third ('cambered') had a single, cambered foil over its entire length and was made from stainless-steel plate (53.0 kg, 1.08 m × 0.73 m, 0.79 $m^2$; Fig. 2c).

The fourth design was the batwing and comprised a main sled made from mild and stainless steel, and a polyurethane (PU) sail set on a stainless-steel boom and mast (60.7 kg, 1.12 m × 1.23 m, 0.74 $m^2$) configured to remain at a 20° AOA (Fig. 2d). The batwing foil was designed to act like an independent kite with a single longitudinal connection to the trawl system via a heavy main sled made from a combination of mild and stainless steel (Fig. 2d). The batwing was configured so that the heavy sled baseplate was aligned to the tow direction, while the sail had a stable AOA and rode on a polyurethane flap designed to pass lightly over the seabed on a layer of pressurised water (similar in concept to the skirt on a hovercraft).

To ensure the same trawl wing-end height during fishing, vertical upper sweep attachment bars were welded to the tops of the flat-rectangular and kilfoil designs to match the heights of the cambered and batwing otter boards (Fig. 2). All otter boards were rigged at their industry-standard AOAs, and to achieve the same trawl wing-end spreads (see Results Section).

### 2.2. Experiment 1 – Four pairs of otter boards with trawls

In the first experiment, the four otter boards were tested against each other in paired comparisons. On each fishing day, one of the six possible otter-board combinations was attached to each side of the vessel. The 41-mm trawls (A and B) and sweeps were clipped to the otter boards, while the Notus paired sensors were attached to the trawl wing ends. After two replicate deployments, the trawl-monitoring equipment (Notus sensors and load cells) were swapped from side-to-side, but the trawls remained. After four replicate deployments, both the trawls and the trawl-monitoring equipment were swapped from side-to-side. After six deployments, just the trawl-monitoring equipment was swapped again. In total, each of the four otter-board pairs were deployed across three alternate replicate days, with eight replicate 30-min deployments for each treatment on each day (providing a total of 24 deployments).

### 2.3. Experiment 2 – Two pairs of otter boards with trawls

To obtain more data over a broader range of conditions (and especially longer tow durations more representative of conventional operations), just the flat-rectangular and batwing otter boards were compared. On each of four days, pairs of the two otter boards were alternately attached to each side of the vessel, and clipped to the sweeps attached to the 32-mm trawls. The smaller-mesh trawls were used to remove the possibility that confounding

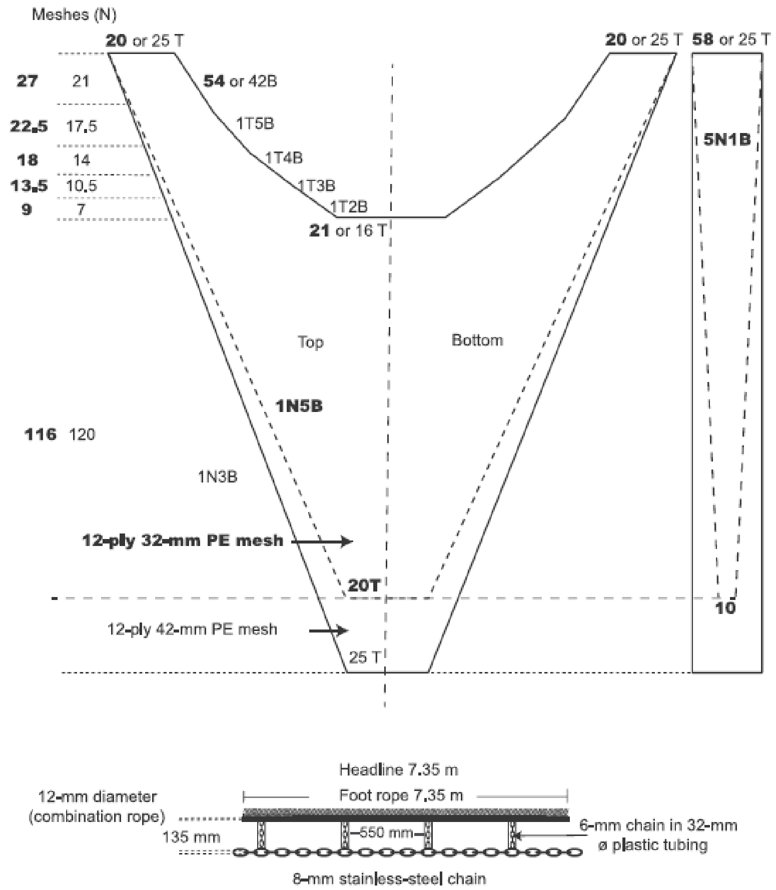


**Fig. 1.** Plans of the 41- and 32-mm trawls used in the study. N, normal; T, transversals; B, Bars; and Ø, diameter (information in bold is specific to the 32-mm trawl).

distortion of the trawls (particularly in the side panels) caused by the strain-equalizing mechanism of the batwing otter boards allowed small school prawns to escape (see Results and Discussion Sections). The trawl monitoring equipment was randomly allocated to one side of the vessel on each day. Five 50-min deployments were completed on each day (i.e. a total of 20 deployments for each otter board), swapping the trawls from side-to-side after the third deployment.

### 2.4. *Experiment 3 – Two pairs of otter boards without trawls*

In experiment 3, the flat-rectangular and batwing otter boards were again tested against each other as for experiment 2, but with the trawls removed to obtain drag estimates for the otter boards only. To limit separation of the otter boards and fix the AOA, two lengths of 3-m stainless steel wire (6-mm Ø) were secured between the upper and lower net attachment points on each otter board pair and a third wire (3.5 m) was connected between each otter-board pair at the warp connection points (Fig. 3). The trawl monitoring equipment was alternately allocated to one side of the vessel on each day (with the Notus paired sensors secured to the outside posterior surface of each otter board; Fig. 3) and between 8 and 12 replicate deployments completed over four days (total $n = 40$).

### 2.5. *Data collected and statistical analyses*

In all three experiments, the technical data collected describing the operational procedures during each deployment included the: (i) drag (kgf) of each gear configuration; (ii) total distance the gears were towed (otter boards on and off the bottom – obtained from the plotter and trawl-monitoring system); (iii) speed over the ground (SOG) and through the water (STW; both in m $s^{-1}$), (iv) water depth (m), (v) distance of the gear configurations behind the vessel, and (vi) wing-end (experiments 1 and 2) or otter-board (experiment 3) spreads (m). All electronic data were recorded at 60-s intervals. For experiments 1 and 2, otter-board AOA was estimated using the otter-board orientation model of Sterling (2000) with inputs of wing-end spread (for each deployment) and used to calculate otter-board span (contact) on the substrate (by multiplying the otter-board length by the sine of the AOA) and ultimately, the effective total bottom contact (average wing-end spread + otter-board lateral baseplate contact).

At the end of each deployment in experiments 1 and 2, all catches were separated by codend, with the total weights of school

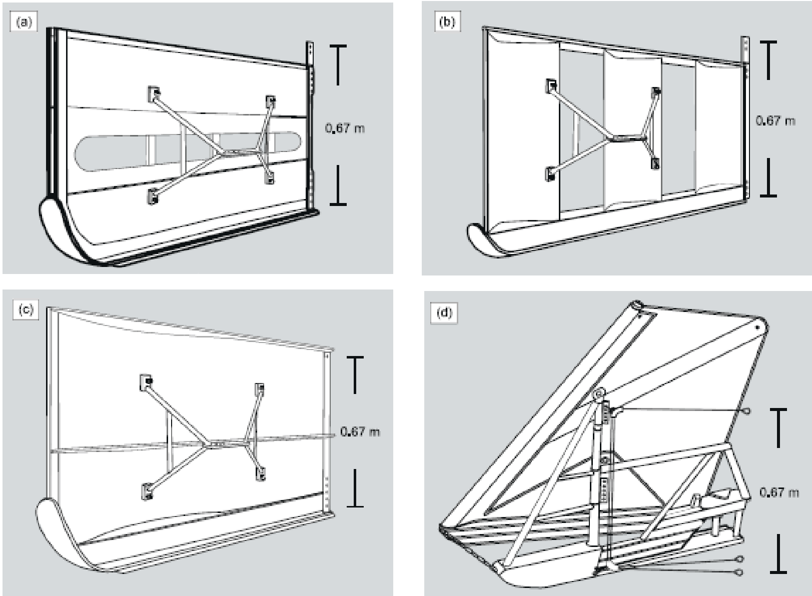


**Fig. 2.** Three-dimensional representation of the (a) flat-rectangular, (b) kilfoil, (c) cambered and (d) batwing otter boards. The 0.67 m represents the sweep-line attachment points.

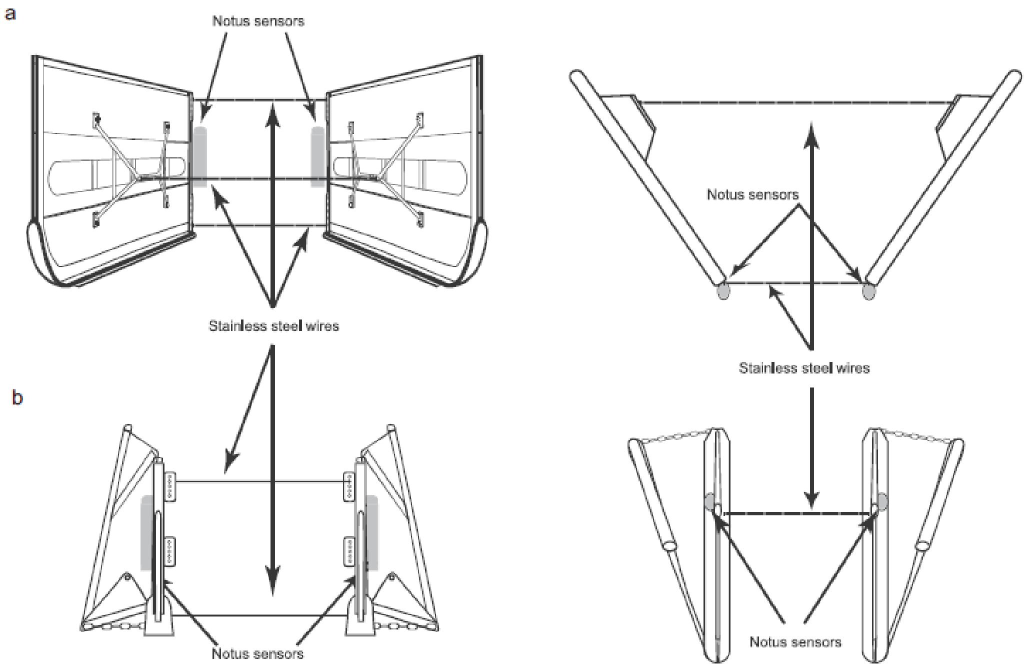


**Fig. 3.** Front and top views of the (a) flat-rectangular and (b) batwing otter boards rigged without a trawl in experiment 3.

**Table 1**
Scientific and common names and numbers of organisms caught during experiments (exp) 1 and 2.

| Family | Scientific name | Common name | Total numbers | |
|---|---|---|---|---|
| | | | Exp 1 | Exp 2 |
| Crustaceans | | | | |
| Palaemonidae | *Macrobrachium novaehollandiae* | Freshwater prawn | 3 | – |
| Penaeidae | *Metapenaeus macleayi* | School prawn | 182,568 | 164,424 |
| | *Penaeus monodon* | Tiger prawn | 1 | |
| Teleosts | | | | |
| Ambassidae | *Ambassis jacksoniensis* | Port Jackson glassfish | 3 | 5 |
| | *Ambassis marianus* | Ramsey's perchlet | 11 | 53 |
| Anguillidae | *Anguilla reinhardtii* | Long-finned eel | 8 | 3 |
| Ariidae | *Arius graeffei* | Forktail catfish | 728 | 86 |
| Apogonidae | *Siphamia roseigaster* | Pink-breasted siphonfish | – | 3 |
| Carangidae | *Pseudocaranx dentex* | Silver trevally | – | 1 |
| Clupeidae | *Herklotsichthys castelnaui* | Southern herring | 275 | 138 |
| | *Hyperlophus vittatus* | Whitebait | 7 | 4 |
| Engraulidae | *Engraulis australis* | Australian anchovy | – | 2 |
| Gerreidae | *Gerres subfasciatus* | Silver biddy | 3 | 27 |
| Megalopidae | *Megalops cyprinoides* | Oxeye herring | – | 3 |
| Monodactylidae | *Monodactylus argenteus* | Diamond fish | 6 | 40 |
| Mugilidae | *Liza argentea* | Flat-tail mullet | – | 1 |
| Paralichthyidae | *Pseudorhombus arsius* | Largetooth flounder | – | 4 |
| Platycephalidae | *Platycephalus fuscus* | Dusky flathead | 1 | 2 |
| Plotosidae | *Euristhmus lepturus* | Longtail catfish | 4 | 3 |
| Pomatomidae | *Pomatomus saltatrix* | Tailor | 12 | 11 |
| Scatophagidae | *Selenotoca multifasciata* | Old maid | 5 | 4 |
| Sciaenidae | *Argyrosomus japonicus* | Mulloway | 184 | 63 |
| Soleidae | *Synclidopus macleayanus* | Narrow banded sole | 81 | 13 |
| Sparidae | *Acanthopagrus australis* | Yellowfin bream | 119 | 750 |
| | Rhabdosargus sarba | Tarwhine | – | 1 |
| Tetrarogidae | *Notesthes robusta* | Bullrout | 33 | 76 |

–, not present in catches.

prawns and bycatch collected along with the numbers of each bycatch species. Total lengths (TL to the nearest 0.5 mm) of the most abundant teleosts were also collected. A random sample of ~500 g of school prawns was collected and a subsample (~100) measured (carapace length – CL in mm) in the laboratory. These data were used to estimate the total numbers caught and mean CL during each deployment.

The technical and biological data were separately analysed within experiments using linear mixed models (LMMs), with some standardised prior to analyses. Numbers and weights were analysed as log-transformed data, after being standardised to per ha trawled calculated using the footrope contact (average wing-end spread × distance trawled) and, additionally where these were significant for school prawns, the effective total-system contact ((i.e. wing-end spread + span of otter-board contact) × the distance trawled) for fishing. The latter was done to test the hypothesis that otter-board contact span explained some of the variability in school prawn catches (see Results Section), and did not include the batwing sleds, because these were outside the effective herding path of the trawl (Broadhurst et al., 2012). All other data, including the mean CL of school prawns per deployment, drag, wing-end spread, SOG, STW and distance trawled were analysed in their raw form.

All models included 'otter-board pair' as a fixed effect while, where appropriate (depending on the experiment), the random effects included 'trawls', 'trawl sides', 'otter-board sides' and 'days' and the interaction between 'deployments' and days. For the LMMs assessing drag and spread, additional random terms involved load cells and the paired Notus sensors, respectively while additional covariates included SOG, 'current' (calculated as the speed of the water in the direction of travel and defined as SOG–STW), distance aft of the trawl configuration from the vessel and fishing depth. All models were fitted using the lmer function from the lme4 package in R 2.15.3 (The R Project for Statistical Computing; http://www.r-project.org/) and the significance of trawl design was determined using a likelihood ratio test (LRT). The LRT was used to compare model log-likelihoods and test whether any differences were statistically significant (Rice, 2006). In experiment 1, where the levels of otter-board pair exceeded two, significant differences were explored using the Benjamini–Hochberg–Yekutieli procedure to control the false discovery rate (FDR; Benjamini and Yekutieli, 2001). The FDR is the expected proportion of false positive discoveries between all of the rejected hypotheses.

Relevant back-transformed predicted means from the LMMs were used to calculate relative fuel consumptions associated with towing the trawls and otter boards in experiments 1 and 2. Specifically, assuming that for any given towing speed, the concomitant fuel usage was proportional to the drag, it is possible to determine relative fuel consumption rate ($L\,h^{-1}$) between each side using the predicted mean drags as determined by the repeated load-cell measurements. Fuel consumption was standardised to per ha trawled (i.e. intensity) and per kg of school prawns caught for each otter-board configuration by comparing the predicted fuel consumption rate with predicted mean wing-end spread (the rate at which area was being swept for a given trawl speed), and the predicted absolute mean school prawn catches (derived by fitting the same model above to the unstandardised log-transformed data) from the respective LMMs.

## 3. Results

School prawns comprised 99% of the total catches in experiments 1 and 2 (Table 1). The minimal bycatch included 25 species, but was dominated by forktail catfish (*Arius graeffei*; 8.0–13.5 cm TL), southern herring (*Herklotsichthys castelnaui*; 7.0–16.0 cm TL) and mulloway (*Argyrosomus japonicas*; 4.5–20.5 cm TL) in experiment 1 (80% of the total catch) and yellowfin bream (*Acanthopagrus australis*; 6.5–23.5 cm TL) and southern herring (7.0–15.5 cm TL) in experiment 2 (64%) (Table 1).

**Table 2**
Summaries of likelihood ratio test (LRT) statistics from linear mixed models assessing the importance of the fixed effect of otter-board pairs in experiments (exp) 1 (flat-rectangular, kilfoil, cambered and batwing attached to identical 41-mm mesh trawls), 2 (flat-rectangular and batwing attached to identical 32-mm mesh trawls) and 3 (flat-rectangular and batwing with no trawls) in explaining variability among key technical and, where relevant, biological responses. Owing to a significant interaction with SOG, no main effect of otter board was presented for drag in experiments 2 and 3 (see Table 3). Numbers and weights were analysed as log-transformed data, after being standardised to per ha trawled calculated using the footrope contact (average wing-end spread × distance trawled) and, additionally where these were significant for the school prawns, the total-system contact ((i.e. wing-end spread + span of otter-board contact) × the distance trawled).

| | LRT | | |
|---|---|---|---|
| | Exp 1 | Exp 2 | Exp 3 |
| Technical variables | | | |
| Wing-end (exp 1 and 2) or otter-board (exp 3) spread | 1.49 | 0.04 | 9.27** |
| Distance trawled | 0.87 | 1.03 | 1.07 |
| Otter-board AOA | 33.46*** | †*** | †*** |
| Total bottom contact | 41.27*** | 7.81** | NA |
| Drag | 9.64* | NA | NA |
| Biological variables | | | |
| Wt of school prawns $ha^{-1}$ of footrope contact | 18.89*** | 0.76 | NA |
| Wt of school prawns $ha^{-1}$ of total-system contact | 9.13* | NA | NA |
| No. of school prawns $ha^{-1}$ of footrope contact | 12.78** | 1.13 | NA |
| No. of school prawns $ha^{-1}$ of total-system contact | 6.02 | NA | NA |
| CL of school prawns | 8.19* | 2.54 | NA |
| Wt of total bycatch $ha^{-1}$ of footrope contact | 0.72 | 0.10 | NA |
| No. of total bycatch $ha^{-1}$ of footrope contact | 1.00 | 0.22 | NA |
| No. of yellowfin bream $ha^{-1}$ of footrope contact | 2.87 | – | NA |
| No. of forktail catfish $ha^{-1}$ of footrope contact | 3.36 | 0.41 | NA |
| No. of southern herring $ha^{-1}$ of footrope contact | 4.47 | 0.42 | NA |
| No. of mulloway $ha^{-1}$ of footrope contact | 0.69 | – | NA |

– not present in sufficient numbers. NA, not applicable for analyses; †, no LRT available because the batwing otter board maintained a constant 20° angle of attack (AOA).
* $p < 0.05$.
** $p < 0.01$.
*** $p < 0.001$.

### 3.1. Experiment 1 – Four pairs of otter boards with trawls

The four otter-board and trawl configurations were towed at a (mean ± SE) SOG of 1.24 ± 0.01 m $s^{-1}$ and STW of 1.43 ± 0.08 m $s^{-1}$. There was no significant difference in the wing-end spreads of the trawls rigged among otter-board pairs, nor distance trawled (LMM, $p > 0.05$; Tables 2 and 3), but otter-board AOAs, total bottom contact and drag were all significantly different (LMMs, $p < 0.01$; Tables 2 and 3). Specifically, while the batwing maintained a 20° AOA, the kilfoil (30.58 ± 0.04°), flat-rectangular (32.83 ± 0.04°) and cambered (38.62 ± 0.04°) designs were spread at significantly (and incrementally) greater AOAs (FDR, $p < 0.05$; Tables 2 and 3). However, the AOAs did not significantly affect the total bottom contact (because the different otter-board lengths offset any relative reductions) among the conventional configurations (FDR, $p > 0.05$; Tables 2 and 3), but all three had significantly greater total bottom contacts than the batwing configuration (up to 1.24 times more; FDR, $p < 0.05$; Table 3). For individual otter boards (from the four designs), a combination of their AOA and length altered (by up to 66%) their projected surface area to between ~0.25 and ~0.48 $m^2$.

The LMM for drag included the fixed effects of otter-board pair, SOG and current, with the former two being significant ($p < 0.05$). To facilitate presentation, the predicated mean drags were calculated at the centred value of SOG (i.e. drag at average SOGs) and for zero current (Table 3). Compared to all three conventional systems, the batwing configuration had significantly less drag (predicted mean reduced by between 14.00 and 18.34%). Further, compared to the kilfoil and cambered otter-board configurations (which had the same drag; FDR, $p > 0.05$; Table 3), there was less drag associated with the flat-rectangular configuration (by 5%; FDR, $p < 0.05$; Table 3). The fuel rate varied between ~5.00 and ~6.13 L $h^{-1}$ while fuel intensity was between ~2.20 and ~2.68 L $ha^{-1}$, with the batwing otter boards requiring the least fuel to tow (Table 3).

For the biological variables, significant differences were limited to school prawn catches, with the most consistent difference being that the batwing configuration retained significantly fewer individuals per ha of footrope contact (by both weight and number) than the conventional configurations (LMM, $p < 0.05$, Table 2, Fig. 4a and b). Standardising catches to per ha of total-system contact (to incorporate the otter-board span on the bottom) eliminated some of the significant differences among the conventional and batwing configurations, but not all (Fig. 4a and b). In particular, the cambered otter-board configuration retained significantly more school prawns by weight (by between 11 and 33%) than the other designs, and also at a significantly smaller mean size (15.22 ± 0.11 mm CL) than the batwing configuration (15.52 ± 0.11 mm CL) (FDR, $p < 0.05$; Fig. 4a). Although not significant, the cambered otter-board configuration also caught a smaller mean CL of school prawns than the kilfoil (15.27 ± 0.11 mm CL) and flat-rectangular (15.34 ± 0.11 mm CL) (FDR, $p > 0.05$). No significant differences were detected for catches of fish (LMM, $p > 0.05$; Table 2, Fig. 4c–g).

### 3.2. Experiment 2 – Two pairs of otter boards with trawls

The flat-rectangular and batwing otter-board configurations were towed at a mean ± SE SOG and STW of 1.29 ± 0.01 and 1.28 ± 0.01 m $s^{-1}$. There was no significant difference in the wing-end spread of the 32-mm mesh trawls rigged between otter-board pairs, nor the distance trawled (LMM, $p > 0.05$; Tables 2 and 3), however like for experiment 1, the AOA, total-bottom contact and drag were all significantly different (LMMs, $p < 0.001$; Tables 2 and 3). The differences between otter-board pairs for AOA, total bottom contact and projected surface area followed those for experiment 1 (Tables 2 and 3). For drag, the parsimonious LMM included a significant interaction between gear and SOG and a significant main effect of current ($p < 0.01$). The predicated mean drags for the two configurations are presented at the centred value of SOG (i.e. drag at average SOGs) and for zero current; under which criteria the batwing configuration had ~15% less drag than the flat-rectangular configuration (Table 3). The fuel rate equated to ~5.28 and ~6.21 L $h^{-1}$ while fuel intensity was ~2.00 and ~2.33 L $ha^{-1}$ for the batwing and flat-rectangular otter boards, respectively (Table 3).

In terms of catches per ha trawled of footrope contact, no significant differences were detected between otter-board configurations

**Table 3**
Summary of predicted mean ± SE wing-end spreads or footrope contact (m), otter-board angles of attack (AOA), otter-board projected area ($m^2$), total bottom (footrope + otter-board baseplate lateral span) contact (m), drags (kgf) and subsequent estimated fuel rates and intensities for four pairs of otter boards (flat-rectangular, kilfoil, cambered and batwing otter boards) attached to identical 41-mm mesh trawls in experiment 1 and two pairs of otter boards (flat-rectangular and batwing) attached to identical 32-mm mesh trawls in experiment 2, and spread, AOA and drags for the pairs of the flat-rectangular and batwing otter boards tested without trawls in experiment 3. Mean predicted drags were derived with a centred value of speed over the ground and with zero current. The predicted areas (of individual otter boards) were derived from the percentage of overall surface area when correcting for AOA. Dissimilar superscript letters within experiments indicate significant differences detected in false-discovery-rate pairwise comparisons (experiment 1) or linear mixed models (experiments 2 and 3).

| | Otter-board pairs | | | |
|---|---|---|---|---|
| | Flat-rectangular | Kilfoil | Cambered | Batwing |
| Experiment 1 – four otter-board pairs with 41-mm mesh trawls | | | | |
| Wing-end spread or footrope contact (m) | 5.08 (0.06)$^A$ | 5.17 (0.06)$^A$ | 5.13 (0.06)$^A$ | 5.10 (0.06)$^A$ |
| Otter-board AOA (°) | 32.83 (0.40)$^C$ | 30.58 (0.40)$^B$ | 38.62 (0.40)$^D$ | 20(0.00)$^A$ |
| Otter-board projected area ($m^2$) | 0.41 | 0.29 | 0.48 | 0.25 |
| Total bottom contact (m) | 6.58 (0.07)$^B$ | 6.44 (0.07)$^B$ | 6.47 (0.07)$^B$ | 5.30 (0.07)$^A$ |
| Drag (kgf) | 251.57 (2.45)$^B$ | 264.94 (3.18)$^C$ | 264.46 (2.46)$^C$ | 216.33 (3.18)$^A$ |
| Fuel rate ($L h^{-1}$) | 5.82 | 6.13 | 6.12 | 5.00 |
| Fuel intensity ($L ha^{-1}$) | 2.57 | 2.66 | 2.68 | 2.20 |
| Experiment 2 – two otter-board pairs with 32-mm mesh trawls | | | | |
| Wing-end spread (m) | 5.17 (0.12)$^A$ | – | – | 5.12 (0.12)$^A$ |
| Otter-board AOA (°) | 33.71 (0.98)$^B$ | – | – | 20(00)$^A$ |
| Otter-board projected area ($m^2$) | 0.42 | – | – | 0.25 |
| Total bottom contact (m) | 6.73 (0.15)$^B$ | – | – | 5.32 (0.15)$^A$ |
| Drag (kgf) | 268.14 (2.08)$^B$ | – | – | 227.93 (2.01)$^A$ |
| Fuel rate ($L h^{-1}$) | 6.21 | – | – | 5.28 |
| Fuel intensity ($L ha^{-1}$) | 2.33 | – | – | 2.00 |
| Experiment 3 – two otter-board pairs without trawls | | | | |
| Otter-board spread (m) | 2.59 (0.10)$^A$ | – | – | 2.92 (0.10)$^B$ |
| Otter-board AOA (°) | 32.59 (2.13)$^B$ | – | – | 20(00)$^A$ |
| Drag (kgf) | 158.65 (3.79)$^B$ | – | – | 116.74 (3.77)$^A$ |

–, not applicable. ($p < 0.05$).

for any of the variables, although the predicted mean weights and numbers of school prawns were 5.07 and 7.67% lower for the batwing configuration (LMM, $p > 0.05$, Tables 2 and 4). Further, although there were few data ($n = 104$), the LRT $p$-value for yellowfin bream catches was 0.09, with a corresponding 1.4 times mean increase in the numbers retained in the batwing configuration (Tables 2 and 4).

### 3.3. Experiment 3 – Two otter boards without trawls

Substituting a trawl with wire stays between the paired flat-rectangular and batwing otter boards presented few logistical problems, with both configurations towed at a mean ± SE SOG and STW of $1.31 \pm 0.01$ and $1.69 \pm 0.06\, m\, s^{-1}$. Compared to the flat-rectangular otter-board pair, the batwing pair were spread significantly wider (11% difference in predicted means) and at a lower AOA ($20 \pm 00°$ vs $32.59 \pm 2.13°$; LMM, $p < 0.01$; Tables 2 and 3). The parsimonious LMM for drag comprised a significant interaction between otter-board configuration and SOG, and a main effect of current ($p < 0.01$; Table 3). At average SOG and for zero current, the predicated mean drag of the batwing pair was 116.75 ± 3.77 kg, or 26% less than that for the flat-rectangular otter board (158.65 ± 3.79 kg; Table 3).

**Table 4**
Predicted mean catch variables per ha trawled of footrope contact (average wing-end spread × distance trawled) in identical 32-mm mesh trawls spread with pairs of flat-rectangular and batwing otter boards.

| Variables | Batwing | Flat-rectangular |
|---|---|---|
| Wt of school prawns $ha^{-1}$ trawled | 5.43 | 5.61 |
| No. of school prawns $ha^{-1}$ trawled | 2044.76 | 2209.02 |
| Wt of total bycatch $ha^{-1}$ trawled | 0.46 | 0.48 |
| No. of total bycatch $ha^{-1}$ trawled | 16.00 | 17.57 |
| No. of yellowfin bream $ha^{-1}$ trawled | 9.61 | 13.37 |
| No. of forktail catfish $ha^{-1}$ trawled | 0.86 | 0.76 |
| No. of southern herring $ha^{-1}$ trawled | 1.74 | 1.43 |

## 4. Discussion

Compared to the conventional otter boards, the batwing consistently demonstrated a superior engineering performance, ultimately manifesting as maintenance of sufficient trawl SR with the least drag and therefore the lowest fuel intensity and rate (up to $2.26\, L\, h^{-1}$ or $0.96\, L\, ha^{-1}$ lower, for double rig in the tested fishery). This result can be attributed to the two key aspects of the batwing's design: (i) a baseplate aligned with the tow direction, which eliminated the shearing force on the bottom; and (ii) the hinged, hydrodynamic wing with a low AOA (20°), which reduced hydrodynamic drag (Sterling and Eayrs, 2010).

The inherent, consistent engineering benefits of the batwing are quite important, given that fuel can represent a large proportion (up to 30%) of a trawler's operating costs (e.g. Thomas et al., 2010). Any reduction in the overall trawl system drag will help to alleviate some of the fuel used during trawling; of which conventional otter boards typically represent anywhere from 30% in single rig configurations (Sterling and Eayrs, 2010) to the 56% estimated here in experiment 3 (by comparing with data from experiment 2). Based on our data for the studied fishery, replacing any of the conventional otter-board pairs with the batwing would reduce fuel while trawling by between 16 and 22%, which would equate to between ~$A 2–3 K per fishing season.

While there are numerous conventional otter-board designs, often incorporating complex foil and camber arrangements, which might similarly reduce hydrodynamic drag and improve efficiency, many fishers still use basic designs like the flat-rectangular (Patterson and Watts, 1985; Sterling, 2000). The popularity of the flat-rectangular otter board among local fishers is supported by the results from experiment 1, with it having the least drag (by ~5%) of the conventional designs. Until recently, in many fisheries, the flat-rectangular otter board was among the most

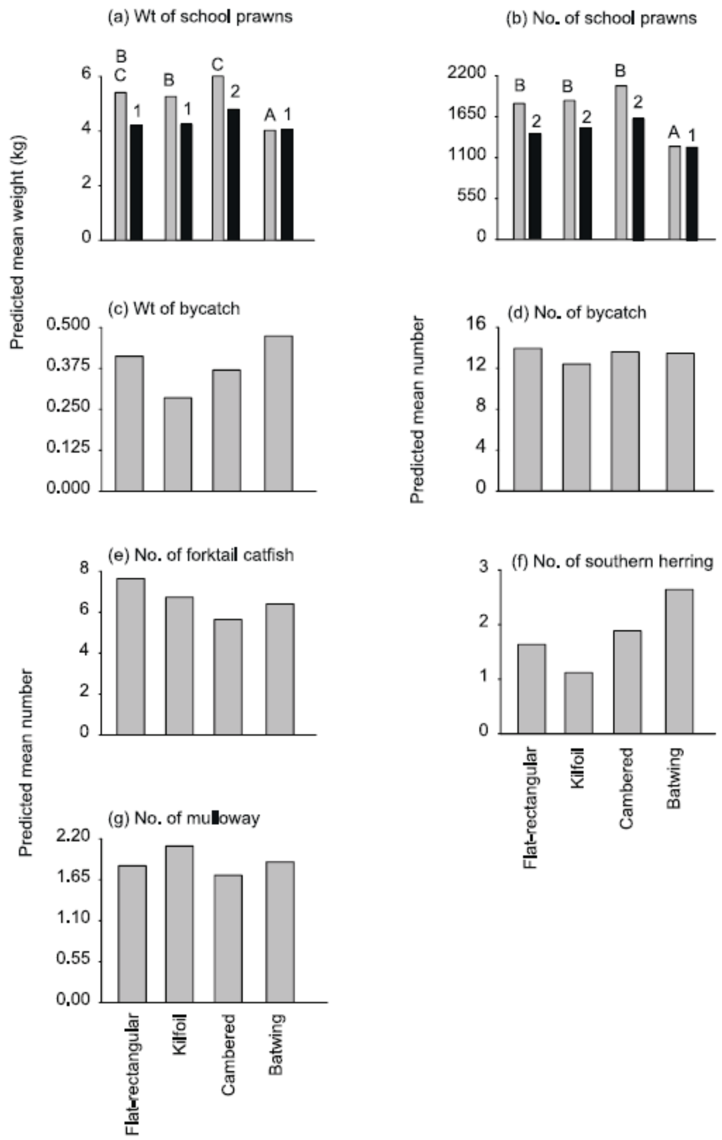


**Fig. 4.** Differences in predicted mean catches per ha trawled of footrope contact (grey histograms) and, where relevant, total-system contact (black histograms) between identical 41-mm mesh trawls spread with pairs of flat-rectangular, kilfoil, cambered and batwing otter boards for the (a) weights and (b) numbers of school prawns (*Metapenaeus macleayi*), (c) weights and (d) numbers of bycatch and numbers of (e) forktail catfish, *Arius graeffei*, (f) southern herring, *Herklotsichthys castelnaui* and (g) mulloway, *Argyrosomus japonicus*. Dissimilar letters and numbers above the histograms indicate significant differences detected in false-discovery-rate pairwise comparisons ($p < 0.05$).

common designs operated (e.g. nearly 100% usage in Australian prawn fisheries until the mid-1980s; Sterling and Eayrs, 2010); reflecting a combination of its simple, easily constructed and maintained design, and comparative efficiency to many contemporary otter boards when operated at 30–40° AOA (e.g. Patterson and Watts, 1985; Seafish et al., 1993).

While it is imperative that otter boards are appropriately rigged to maximise hydrodynamic performance (Sterling and Eayrs, 2010), their overall length is also important in terms of habitat impacts. For example, the cambered otter boards tested in experiment 1 had high substrate contact (~62% of their length at the average 38.62° AOA). The batwing offers a real solution to minimising habitat impacts by having its main substrate contact (the sled) aligned in the direction of towing. Specifically, a conventional otter board 1.12 m long (the same as the batwing) operating at a typical AOA of 35–40° will have ~0.64–0.72 m of lateral contact compared to the ~0.1 m wide baseplate (assuming minimal habitat disturbance of the 'flap') for the batwing. Using an otter board with a fixed (or low) AOA would also reduce system contact, but as demonstrated in experiment 1, a combination of AOA and otter-board length needs to be considered, because a long otter board at a shallow AOA could still contact more of the sea bed than a short design at a more acute AOA.

While reducing total system contact via otter-board configurations may help to mitigate habitat impacts, a concomitant effect could be reduced catches of penaeids (Broadhurst et al., 2012). The cambered otter boards currently are the preferred design in the Clarence River fishery – primarily because they are perceived to catch more school prawns (supported by the results here) than other contemporary designs, which may in part result from their substantial ground contact. However, it is also possible that their large projected surface area (in the direction of the tow) is important. Specifically, this design had more projected area (~18–95% or ~0.07–0.24 $m^2$ after adjusting for AOA) than the other otter-board designs. Even a small increase in projected area may have directed more school prawns towards the trawl mouth. Such effects might also explain why, despite the lower substrate contact, the batwing maintained catches of school prawns in experiment 2. Specifically, the large sail and flap might have deflected some individuals close to the substratum into the trawls.

While the cambered otter boards improved school prawn catches, this was somewhat offset by their lower fuel efficiency than the flat-rectangular design. Such a result supports the concept that before implementing new otter-board designs (or other modifications), an holistic approach is necessary that allows profit margins to be maintained while increasing ecological efficiency. A comprehensive set of experiments (e.g. testing with a variety of trawl designs in different fisheries) is required; otherwise fishers are unlikely to commit to the continued use of new designs over the long term (Jennings and Revill, 2007).

It is also clear that introducing any technical modification requires careful adjustment and refinement across as broad a range of conditions as possible prior to use. For example, in experiment 1, the batwing was associated with significantly lower catches of school prawns than the conventional otter-board designs. We attributed this result to the more dynamic net attachment points – movable wire cables instead of fixed points on conventional designs – which may have permitted the trawl wing to operate slightly higher in the water column, allowing sustained lateral opening of the meshes down the sides of the trawl – thus increasing escape opportunities. Using the batwing and flat-rectangular boards with the smaller (32 mm) meshed trawls in experiment 2 negated these issues and resulted in catches not being significant different for the two otter board types. The importance of electronic monitoring equipment (e.g. Notus sensors and fuel meters) was reinforced by observing that changing to the smaller mesh trawl did not affect the relative differences in performance (e.g. wing-end spread, drag and fuel rates) between experiments.

The results from this study suggest that the batwing otter board has good potential for reducing fuel consumption while maintaining the catching performances of the assessed penaeid trawls. Using otter boards with minimal substrate contact (such as the batwing) will also potentially reduce damage to trawled areas (van Marlen et al., 2010). While creating the definitive otter board may ultimately be difficult to achieve, we believe that to make significant improvements to overall trawl efficiency it may be more conducive to focus further research on an otter-board design that has already attained satisfactory engineering performance (e.g. the batwing) and work on improving its catching performance. The pair of batwings tested here would cost ~$A 3 K which is comparable to purchasing a pair of flat-rectangular otter boards and ~$A 2 K less than the cambered otter boards. Batwing maintenance is equivalent to other otter boards, which combined with their superior fuel efficiency, should facilitate quicker investment returns (i.e. within ~one season, depending on which otter-board design they are replacing).

Alternatively, it might be advantageous to investigate the possibility of modifying existing designs – perhaps to incorporate the key mechanisms of designs such as the batwing to improve engineering and/or catching performances. While not specifically tested, based on our results, an otter board with superior engineering performance will also likely have a lower AOA, which has concomitant potential for reducing habitat impacts (Sterling and Eayrs, 2008; van Marlen et al., 2010).

## Acknowledgements

This study was funded by the New South Wales (NSW) Department of Primary Industries and the Australian Fisheries Research and Development Corporation (FRDC; Grant no. 2011/010). Funding for developing and implementing the batwing otter board was provided by the World Wildlife Fund PA 01, PA 17; Enviro fund 62463; FRDC 2004/060, 2008/079. Thanks are extended to the (NSW) Professional Fisher's Association, Greg Skilleter, Steve Everson, Don Johnson, Jen Marshall, Chris Barnes, Mitch Burns, Nick Sarapuk, and especially Craig Brand.

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**Appendix 9.** Broadhurst, M.K., Sterling, D.J. and Millar, R.B. 2015. Modifying otter boards to reduce bottom contact: effects on catches and efficiencies of triple-rigged penaeid trawls. Fish. Man. Ecol. 22: 407–418

Fisheries Management and Ecology

*Fisheries Management and Ecology*, 2015, 22, 407–418

# Modifying otter boards to reduce bottom contact: effects on catches and efficiencies of triple-rigged penaeid trawls

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**Abstract** Two otter-board modifications designed to minimise bottom contact (and therefore habitat impacts) were compared against conventional otter boards for their relative effects on the engineering and catching efficiencies of triple-rigged penaeid trawls. The first modification involved restricting the angle of attack (AOA) of a flat–rectangular otter board to <30° by attaching a restraining line to an adjacent sled, while the second was a 'batwing' otter board comprising a sled-and-sail assembly operating at 20° AOA. The modifications reduced otter-board bottom contact by up to 8 ha over a night's fishing without affecting standardised catches (per ha) of the targeted eastern king prawns, *Penaeus plebejus*, nor the fuel required. Further, compared to all other trawls, the restrained trawls caught less discarded bycatch (by up to 37%), while the trawls spread by the modified flat–rectangular and batwing otter boards caught more individuals of three retained benthic teleost species per ha than the conventional configuration; results that were attributed to species-specific herding responses. Both modifications represent simple alternatives where there are concerns over either benthic impacts or, for the restraining line, unwanted bycatches in penaeid-trawl fisheries.

KEYWORDS: bycatch reduction, habitat impacts, otter boards, penaeids, selectivity.

## Introduction

More than 100 penaeid species are targeted worldwide using either single or multiple (double-, dual-, triple- or quad-rig) small-meshed [30- to 50-mm stretched mesh opening (SMO)] trawls deployed from vessels <25 m in length (Vendeville 1990; Gillett 2008; Broadhurst *et al.* 2013a,b). Most penaeid trawls have spreading mechanisms involving 'otter boards' which, to ensure sufficient benthic contact, comprise a substantial weight of the entire system. Otter boards are orientated obliquely (i.e. at a so-called angle of attack (AOA) typically between 20 and 45°) so that their hydrodynamic force (>30% of the entire system drag) horizontally spreads the trawls (Patterson & Watts 1986; Sala *et al.* 2009; McHugh *et al.* 2015a).

The simplest otter-board designs have a low aspect ratio (about 0.5) and are flat and rectangular and typically work at a high AOA (35–45°), which although not required to spread the trawls during fishing (i.e. 30° is most effective, while ~20° is the most efficient) ensures their stability during deployment between the vessel and the seabed (Sterling & Eayrs 2010). Improved otter boards would maintain a 15–20° AOA during both deployment and

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doi: 10.1111/fme.12140 

fishing and typically have a greater aspect ratio to suit a lower operating angle (Sterling & Eayrs 2010). Such otter boards should have lower drag, but equally important, proportionally less benthic contact for any given length (McHugh *et al*. 2015a). Minimising the benthic contact of otter boards is an important consideration in some fisheries – primarily because the associated seabed tracks are the most discernible physical impact of demersal trawls – and while few quantitative data are available, there are widespread concerns over associated trophic impacts (Caddy 1973; Kaiser *et al.* 2002).

One novel otter-board design that achieves a consistent low AOA is the 'batwing' (Sterling & Eayrs 2010; McHugh *et al.* 2015a,b). The batwing foil – comprising a polyurethane (PU) sail set on a stainless steel boom and mast – acts like a kite with a single longitudinal connection to the trawl system via a heavy main sled made from mild and stainless steel (and with a similar or lower total weight than conventional otter boards). The batwing is configured so that the sled base plate aligns to the tow direction, while the sail has a stable AOA and rides on a PU 'flap' that passes lightly over the seabed on a layer of high-pressure water for most of its length (video observations by David Sterling). McHugh *et al.* (2015c) demonstrated that by restricting bottom contact to the width of the base plate only, the batwing evokes minimal substrate disturbance.

A recent experiment on board a double-rigged trawler revealed that compared with conventional flat–rectangular otter boards, the batwing reduced drag by up to 18% with no loss of spreading force (McHugh *et al.* 2015a). The batwing did not significantly affect catches in the attached trawls, although slightly fewer school prawns, *Metapenaeus macleayi* (Haswell) (~7% less), and more individuals of one teleost, yellowfin bream, *Acanthopagrus australis* (Owen) (1.4 times), were retained, possibly due to the reduced bottom contact (affecting school prawns) and greater aspect ratio (manifesting as increased visual stimulus and affecting fish). The implications of reduced bottom contact were quantified in a subsequent study, which showed that the batwing displaced dramatically less benthic material (debris) and school prawns than a conventional flat–rectangular otter board with similar spreading force (McHugh *et al.* 2015c). However, while the above results are positive, the batwing has not been formally tested among the various other multitrawl configurations (especially triple- and quad-rigs) – an inherent prerequisite to determining its broader functionality.

In addition to the benefits of the batwing, conceivably there are simple modifications to conventional flat–rectangular otter boards that might be used to consistently lower their AOA (and bottom contact) and possibly improve efficiencies. One option might be to calculate the desired spread ratio (SR; defined as the wing-end spread divided by the stretched head-rope length) of a trawl and then secure an appropriate length of line between the leading edge of paired flat–rectangular otter boards (or an otter board and sled for triple or quad rig) so that the AOA is restricted during fishing. Similar 'restraining lines' have been attached to fish survey trawls to regulate net spread, albeit considerably anterior to the otter boards (e.g. on the warps; Rose & Nunnallee 1996). Beyond regulating AOA, the benefits of a restraining line between the otter boards might include fewer catches of some fish, via the visual stimuli of the horizontal line (termed a 'simple anterior fish excluder' or 'SAFE' by McHugh *et al.* 2014, 2015b). However, there are few available data to support or refute these proposed dual effects of reducing otter-board bottom contact and unwanted catches via a restraining line.

The aims of this experiment were to address the above information shortfall by comparing three otter-board configurations in an Australian, multispecies penaeid-trawl fishery that uses triple-rigged trawls (a configuration used by some 250 vessels or ~20% of the national fleet) to target mostly eastern king prawns, ***Penaeus plebejus*** (Hess), and also several species of commercially important 'by-product' (comprising other legally retained crustaceans, teleosts and cephalopods described by Kennelly *et al.* 1998). More specifically, the hypothesis of no differences in the engineering and catching performances of traditional rectangular flat otter boards rigged: (1) with and (2) without a restraining line to limit SR, and (3) the batwing design was tested.

## Materials and methods

### *Vessel, equipment and trawls used*

The experiment was completed over nine nights (eight of which were consecutive) during July 2014 in oceanic waters off Yamba, south-eastern Australia (29° 26′S; 153° 22′E) using a local, triple-rigged trawler (15.8 m and 128 kw; Fig. 1a). The trawler had 10-mm-diameter (Ø) galvanised steel warps and 73-m bridles (10-mm-Ø galvanised wire) on two hydraulic winches. On-board electronic equipment included a fuel monitor (Floscan series 9000); global positioning system (GPS; Lowrance, Sydney, NSW, Australia); two hull-mounted speed gauges (EchoPilot, Bronze Log+), attachable warp load cells and associated data logger (model nos PA6139 and TP4; Amalgamated Instrument Company, Sydney, NSW, Australia); and a trawl-spread monitoring system (Model

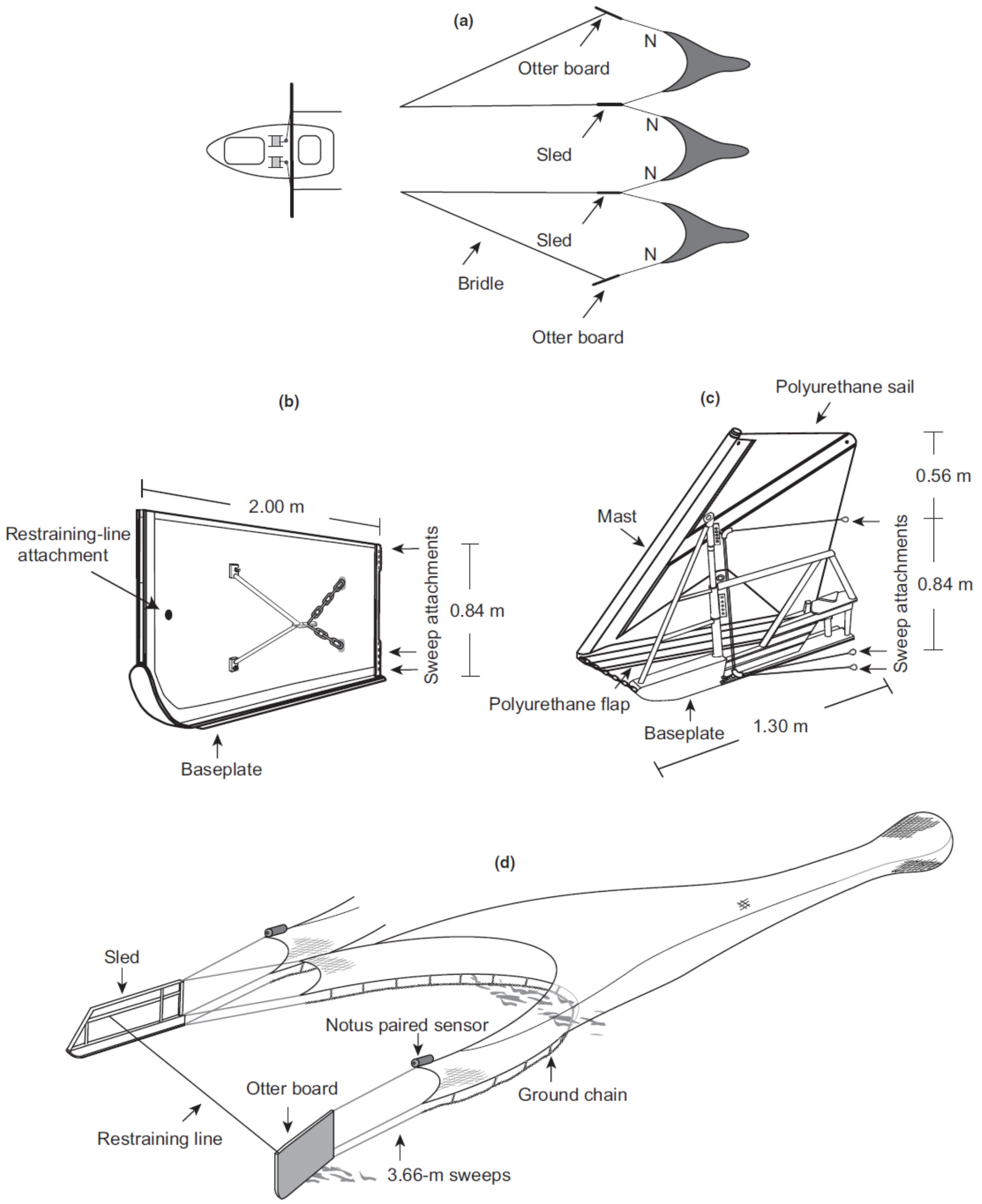


**Figure 1.** Schematic representation of the (a) the triple-rig configuration with the location of the Notus (N) paired sensors, (b) flat–rectangular and (c) batwing otter boards, and (d) portside trawl with the restraining line attached between the sled and flat–rectangular otter board.

no. TM800ET; Notus Trawlmaster System, St Johns, Newfoundland, Canada). The Notus system comprised a computer processing unit, vessel-mounted omnidirectional hydrophone and two cylindrical transducers and associated slaves (each 330 mm long × 77 mm Ø; 1.1 kg in water); all designed to be mounted onto the wing ends of each of the side and the centre trawls (Fig. 1a).

The three trawls used were four-seam Florida Flyer designs made to identical specifications from 47-mm [stretched mesh opening (SMO)] mesh [1.3-mm-Ø polyethylene (PE) twine] in the bodies, and each had headline lengths measuring 12.8 m (individual twine areas were 13.8 $m^2$). Each trawl had ground gear comprising 135-mm, 6-mm-Ø stainless-steel drop chains attached to combination rope, with lead weights and 10-mm stainless-steel chains, a body taper of 1N3B and was attached to an extension section (46-mm SMO, twisted 1.2-mm-Ø PE twine and measuring 100 T × 33 N) with a composite square-mesh panel bycatch reduction device (BRD; Broadhurst & Kennelly 1997) and codend (42-mm SMO, braided 2.0-mm-Ø PE twine and 150 T × 25 N). The trawls were shackled to 3.7-m stainless-steel wire (6 mm Ø) sweeps terminating in clips for attachment to the otter boards and sleds.

### *Otter board configurations and testing*

The trawls were tested with three otter-board configurations, all with the same sleds (stainless steel; 220 kg and 2.13 × 0.91 m each) (Fig. 1b, c). The first two configurations comprised the same flat–rectangular otter boards made from galvanised steel and timber inserts, each measuring 2.00 × 0.84 m and weighing 180 kg (Fig. 1b). The first treatment ('conventional') involved rigging the flat–rectangular conventionally (with the towing point set at 42°). For the second treatment (termed restricted flat–rectangular), a line (8-mm-Ø PE braided rope) was secured between an attachment point at the anterior leading edge of the otter board and across the trawl opening to the closest sled (Fig. 1b, d). The length of line was calculated at 15 m, based on the known otter-board spread (measured during conventional deployments of the flat–rectangular otter boards), and designed to restrict the otter-board AOA to <30° (Fig. 1d). The third design was the batwing and comprised a main sled made from mild and stainless steel, and a PU sail on a stainless-steel boom and mast (120 kg; 1.40 × 1.30 m; and 1.15 $m^2$) configured to remain at a 20° AOA (Fig. 1c). All otter boards and sleds had the same upper and lower sweep attachments to ensure consistent vertical fishing heights and 150- and 100-mm base plates, respectively.

At the start of each night, one of the three otter-board configurations was attached to the sweeps on the triple-rigged trawls. A Notus transducer and slave were secured to the outer wing ends of the two side trawls and the wing ends of the centre trawl (Fig. 1d). The triple rig was then repeatedly deployed for five attempted 120-min deployments on each night between 17:00 and 05:30. On the following day, the otter-board configuration was changed and the Notus paired sensors were also swapped (between the centre and side trawls). Over 9 days, three replicate nights of each configuration, providing 15 replicate deployments, were completed.

### *Data collected and analyses*

The technical data collected during each deployment included the (1) drag of each configuration (kgf); (2) fuel consumed per deployment (L; period between otter boards on and off the bottom); (3) distance trawled (m; otter boards on and off the bottom – obtained from the plotter and net monitoring system); (4) speed over the ground (SOG) and through the water (STW; both in m $s^{-1}$); (5) depth of fishing (m); (6) distance of the trawls behind the vessel (m); and (7) the wing-end spreads (m) (Fig. 2). Drag, speed and wing-end spreads were recorded at 1-min intervals.

The combined wing-end spreads for the side trawls (analysed as one variable—see below) were calculated after adjusting for the span of the sleds, sweeps and the centre trawl (which was distinguishable from the entire system; Figs 1a and 2). Predicted wing-end spreads were used to calculate otter-board AOA (from the model proposed by Sterling 2005) and subsequent lateral benthic contact (Fig. 2; by multiplying the otter-board length by the sine of the AOA).

At the end of each deployment, the catches from each of the three trawls were individually separated into (1) eastern king prawns, and total (2) by-product (other legally retained catches of crustaceans, teleosts and cephalopods) and (3) bycatch (species and/or sizes that had no commercial value or were illegal to retain) and then weighed (Fig. 2). Catches within these categories were then combined across all three trawls (i.e. to provide catches for the entire triple rig), with the numbers and weights of each by-product and bycatch (via sub sampling) species, and total lengths (TL in mm) of the most abundant teleosts recorded (i.e. from the total catch; Fig. 2). Random samples of ~50 eastern king prawns (pooled across all three trawls) in each deployment were measured [carapace length (CL) in mm], weighed and used to estimate the total number and mean CL caught from each otter-board configuration during each deployment.

Prior to analyses, the weights of eastern king prawns, by-product and bycatch from each of the three trawls

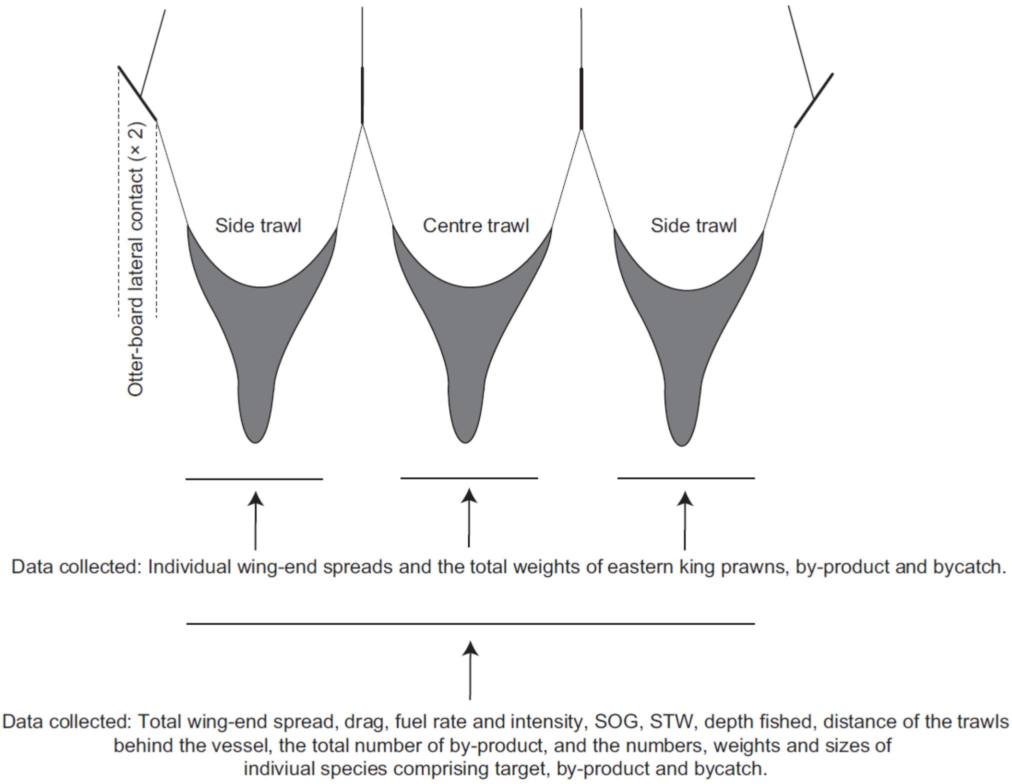


**Figure 2.** Two-dimensional representation of the otter-board lateral bottom contact and technical and biological data collected during the experiment. SOG, speed across the ground (m $s^{-1}$), and STW, speed through the water (m $s^{-1}$). Depth and distances in m, drag in kgf, weights in kg, and fuel rate and intensity in L $h^{-1}$ and $ha^{-1}$, respectively.

within each otter-board configuration were standardised to per ha trawled (using the swept area between the wing ends multiplied by the distance trawled) and then log-transformed (so that effects would act multiplicatively). Data for individual species (combined across the three trawls; Fig. 2) were treated as above, but standardised to per ha trawled using the total system wing-end spread (i.e. sum of the side and centre trawls). The remaining data (including mean CL and TLs for species caught in sufficient quantities, drag, wing-end spread, SOG, ha trawled and fuel used) were analysed in their raw form.

Linear mixed models (LMMs) were fitted to explain variability among responses describing the performance of otter-board configurations. These LMMs specified 'nights' and 'sensors' as random effects to avoid pseudo-replication arising from the possibility of between-day variation or variability between the Notus sensors (Millar & Anderson 2004; Millar *et al.* 2004). Linear mixed models fitted to biological variables had 'otter boards' and 'depth' as potential fixed effects explanatory variables. Statistical significance was determined using likelihood ratio tests (LRTs). Linear mixed models fitted to technical variables considered the additional explanatory variables of SOG and 'current' (calculated as the speed of the current in the direction of travel and defined as SOG–STW).

A smaller, second set of LMMs was fitted to examine the variability of key response variables between the three trawls within each deployment. These LMMs used the same covariates as described above, but with the addition of a trawl (side or centre) effect, and the interaction of trawl with otter board.

All models were fitted using the lmer function from the lme4 package of the R statistical language. Inclusion of effects in the final model was determined using forward selection based on statistical significance at the 5% level using LRTs. Significant pairwise differences among the three otter boards were subsequently explored using the Benjamini–Hochberg–Yekutieli procedure to control the false-discovery rate (FDR; Benjamini & Yekutieli 2001) of the three corresponding tests for pairwise differences (conventional vs restricted flat–rectangular; conventional flat–rectangular vs batwing; and restricted flat–rectangular vs batwing otter boards). This procedure ensured that the type I error rate of 0.05 was preserved simultaneously across all three pairwise comparisons in the sense that the probability (under the null hypothesis of no difference between order boards) of any false positive from the three comparisons is 0.05. Means for the main effect of otter boards are presented with any of the significant continuous covariates centred (mean zero).

## Results

Fifteen replicate deployments of each otter-board configuration were successfully completed, all of which were 120 min in duration, except four (90, 95, 105 and 110 mins). Total catches from the 45 deployments included 351, 1233 and 3288 kg of eastern king prawns, by-product and bycatch, respectively and representative of conventional fishing. The by-product and bycatch comprised 23 and >25 species, respectively, with 12 caught in sufficient quantities to enable meaningful analyses (Table 1). Based on sizes, some species had individuals comprising both bycatch and by-product (Table 1).

### *Engineering performances*

The trawls were towed across average (±SE) SOGs, depths and distances of 1.21 ± 0.02 m $s^{-1}$, 54.94 ± 1.55 m and 8.59 ± 0.13 km, respectively. The parsimonious LMMs describing wing-end spread for the side trawls (which ranged from 8.17 to 10.42 m), centre trawls (7.92 to 11.13 m) and the total system (24.46–31.35 m) comprised the significant main effects of otter boards, depth, SOG and current ($P < 0.05$; Table 1).

Irrespective of the otter boards, the side, centre and total system wing-end spreads were positively affected by both depth and current and negatively affected by SOG (LMM, $P < 0.05$; Table 1). For the main effect of otter boards (and across all other factors), there were incrementally lower side- and total wing-end spreads between the conventional flat–rectangular (9.87 ± 0.06 and 29.43 ± 0.18 m, respectively), restrained flat–rectangular (9.29 ± 0.05 and 28.43 ± 0.15 m) and batwing (8.58 ± 0.06 and 26.17 ± 0.18 m) otter boards (FDR, $P < 0.05$; Tables 1–3, Fig. 3). The significant differences among total wind-end spread were also maintained in the LMM incorporating within-deployment differences ($P < 0.001$; Table 2). However, among the centre trawls, wing-end spreads for the conventional (9.68 ± 0.13 m) and restrained flat–rectangular (9.85 ± 0.11 m) otter boards were not significantly different (FDR, $P > 0.05$), but both were greater than that for the batwing otter boards (9.01 ± 0.13 m) (FDR, $P < 0.05$; Table 1, Fig. 3).

There was a significant difference in the SOG among otter-board configurations, with the restrained flat–rectangular (1.22 ± 0.02 m $s^{-1}$) and batwing (1.26 ± 0.02 m $s^{-1}$) similarly towed slightly faster than the conventional flat–rectangular (1.16 ± 0.18 m $s^{-1}$) otter boards (FDR and LMM, $P < 0.01$; Tables 1 and 3). The areas trawled were also significantly different among treatments, with greater areas by the conventional flat–rectangular (25.03 ± 0.60 ha) and restrained flat–rectangular (24.44 ± 0.60 ha) configurations, than the batwing (22.55 ± 0.60 ha) (FDR and LMM, $P < 0.05$; Tables 1 and 3). Based on analysis of the wing-end spreads, the mean ± SE AOAs were estimated as 40.18 ± 0.36, 22.74 ± 0.65 and 20 ± 00° for the conventional and restrained flat–rectangular and batwing otter boards, respectively, and with corresponding total (i.e. otter-board pair) lateral bottom contacts of 2.58 ± 0.02, 1.54 ± 0.02 and 0.30 ± 0.00 m, respectively (Table 3).

The total system drag was best described by a LMM with otter boards, depth and SOG, all of which were significant ($P < 0.05$; Tables 1 and 3). For all three otter-board configurations, drag increased with depth and SOG and was significantly less for the batwing (1267.80 ± 15.79 kgf) than the conventional (1341.28 ± 16.00 kgf) and restrained flat–rectangular (1361.37 ± 13.84 kgf) otter boards (FDR, $P < 0.05$; Tables 1 and 3).

Both fuel per hour (rate) and ha trawled (intensity) had LMMs restricted to the fixed effect of otter boards, which was not significant ($P > 0.05$; Tables 1 and 3), but on average, the batwing had a slightly lower fuel rate (29.29 ± 0.79 L $h^{-1}$) than the conventional (29.90 ± 0.79 L $h^{-1}$) and restrained flat–rectangular otter boards (31.33 ± 0.70 L $h^{-1}$). All three configurations had similar intensities (2.56 ± 0.08, 2.40 ± 0.09 and 2.52 ± 0.07 L $ha^{-1}$, respectively) (Tables 1 and 3).

### *Catching performances*

There were no significant differences in the catches of eastern king prawns or by-product $ha^{-1}$ among any of the trawls due to otter boards (LMM, $P < 0.05$; Tables 1

**Table 1.** Summaries of fixed effects in linear mixed models (LMM) and likelihood ratio tests (LRT) assessing the significance of otter boards on technical and biological variables. Linear mixed models for biological variables considered otter board and depth as potential explanatory variables, while those for technical variables also considered speed over the ground (SOG) and current (where relevant). Numbers and weights were standardised to per ha trawled, calculated using the wing-end spread (per deployment) of either the side trawls (assumed to be the same), centre trawl or total system (all trawls combined) and then log-transformed before analyses. ret., retained; disc., discarded; EBSF = eastern blue-spotted flathead, STF = small toothed flounder

| | Significant fixed effects in LMM | LRT for otter boards |
|---|---|---|
| Technical variables | | |
| Side-trawls spread (m) | Otter boards, depth, SOG and current | 30.76*** |
| Centre-trawl spread (m) | Otter boards, depth, SOG and current | 12.7** |
| Total system wing-end spread (m) | Otter boards, depth, SOG and current | 32.99*** |
| Speed over the ground (m $s^{-1}$) | Otter boards and current | 11.96** |
| Hectare trawled | Otter boards | 8.46* |
| Drag | Otter boards, depth and SOG | 20.22** |
| Fuel rate (L $h^{-1}$) | | 3.52 |
| Fuel intensity (L $ha^{-1}$) | | 1.55 |
| Biological variables | | |
| Wt of eastern king prawns, *Penaeus plebejus* $ha^{-1}$ side trawls | | 1.00 |
| Wt of eastern king prawns, $ha^{-1}$ centre trawl | | 0.70 |
| Wt of eastern king prawns $ha^{-1}$ total system | | 0.88 |
| No. of eastern king prawns $ha^{-1}$ total system | | 1.97 |
| Mean CL of eastern king prawns total system | | 0.99 |
| Wt of by-product $ha^{-1}$ side trawls | Depth | 0.38 |
| Wt of by-product $ha^{-1}$ centre trawl | | 0.46 |
| Wt of by-product $ha^{-1}$ total system | Depth | 0.42 |
| No. of by-product $ha^{-1}$ total system | | 0.41 |
| Wt of bycatch $ha^{-1}$ side trawls | Otter boards and depth | 6.40* |
| Wt of bycatch $ha^{-1}$ centre trawl | Depth | 5.06 |
| Wt of bycatch $ha^{-1}$ total system | Depth | 5.45 |
| No. of bycatch species total system | Depth | 4.17 |
| No. of ret. cuttlefish, *Sepia* spp. $ha^{-1}$ total system | Depth | 1.98 |
| Wt of ret. cuttlefish $ha^{-1}$ total system | | 1.84 |
| No. of ret. smooth bugs, *Ibacus chacei* $ha^{-1}$ total system | Depth | 0.64 |
| Wt of ret. smooth bugs $ha^{-1}$ total system | Depth | 0.26 |
| No. of ret. octopus, *Octopus* sp $ha^{-1}$ total system | Depth | 3.20 |
| Wt of ret. octopus $ha^{-1}$ total system | Depth | 2.65 |
| No. of ret. red mullet, *Upeneichthys lineatus* $ha^{-1}$ total system | | 0.08 |
| Wt of ret. red mullet $ha^{-1}$ total system | | 0.14 |
| Mean TL of ret. red mullet total system | | 0.08 |
| No. of ret. EBSF, *Platycephalus caeruleopunctatus* $ha^{-1}$ total system | | 4.34 |
| Wt of ret. EBSF $ha^{-1}$ total system | Otter boards | 6.74* |
| No. of ret. leatherjacket, *Nelusetta ayraudi* $ha^{-1}$ total system | Otter boards | 6.50* |
| Wt of ret. leatherjacket $ha^{-1}$ total system | Otter boards | 6.67* |
| No. of ret. red spot whiting, *Sillago flindersi* $ha^{-1}$ total system | | 0.11 |
| Wt of ret. red spot whiting $ha^{-1}$ total system | | 0.07 |
| Mean TL of red spot whiting total system | | 1.58 |
| No. of disc. cuttlefish $ha^{-1}$ total system | | 1.97 |
| Wt. of disc. cuttlefish $ha^{-1}$ total system | | 0.86 |
| No. of disc. EBSF $ha^{-1}$ total system | Depth | 0.89 |
| Wt of disc. EBSF $ha^{-1}$ total system | Depth | 1.51 |
| Mean TL of disc. EBSF $ha^{-1}$ total system | Depth | 5.22 |
| No. of disc. gurnard, *Lepidotrigla argus* $ha^{-1}$ total system | | 0.12 |
| Wt of disc. gurnard $ha^{-1}$ total system | | 0.31 |
| Mean TL of disc. gurnard total system | | 2.31 |
| No. of disc. big redeye, *Priacanthus macracanthus* $ha^{-1}$ total system | | 1.53 |
| Wt of disc. big redeye $ha^{-1}$ total system | | 0.50 |

(continued)

*Table 1. (continued)*

| | Significant fixed effects in LMM | LRT for otter boards |
|---|---|---|
| Mean TL of disc. big redeye total system | Depth | 1.26 |
| No. of disc. long-spine flathead, *Platycephalus longispinis* $ha^{-1}$ total system | Depth | 0.64 |
| Wt. of disc. long-spine flathead $ha^{-1}$ total system | Depth | 0.35 |
| Mean TL of disc. long-spine flathead total system | Depth | 0.05 |
| No. of disc. STF, *Pseudorhombus jenynsii* $ha^{-1}$ total system | Depth | 3.53 |
| Wt of disc. STF $ha^{-1}$ total system | | 2.11 |
| Mean TL of disc. STF $ha^{-1}$ total system | Depth | 2.10 |
| No. of disc. spiky flathead, *Ratabulus diversidens* $ha^{-1}$ total system | Otter boards | 8.88* |
| Wt of disc. spiky flathead $ha^{-1}$ total system | Otter boards | 8.54* |
| Mean TL of spiky flathead total system | | 0.76 |

*$P < 0.05$; **$P < 0.01$; ***$P < 0.001$.

**Table 2.** Summaries of fixed effects in linear mixed models (LMM) and likelihood ratio tests (LRT) assessing the significance of otter boards on within-deployment differences in spread and key biological variables

| Variables | Fixed effects in LMM | LRT |
|---|---|---|
| Total wing-end spread (m) | Otter boards, trawl, otter boards × trawl, depth, SOG and current | 62.25*** |
| Wt of eastern king prawns, *Penaeus plebejus* $ha^{-1}$ | Trawl and depth | 0.87 |
| Wt of by-product $ha^{-1}$ | Trawl and depth | 0.37 |
| Wt of bycatch $ha^{-1}$ | Otter boards, trawl and otter boards × trawl and depth | 30.37*** |

***$P < 0.001$.

and 2, Fig. 4a, b). There was a significant LRT for the weight of bycatch $ha^{-1}$ caught in the side trawls among otter boards (LMM, $P < 0.05$, Tables 1 and 2), and although the predicted means (from the LMM) were not significantly different, the side trawls spread by the restrained flat–rectangular otter boards (i.e. those with the line across the trawl mouth) retained 37 and 19% less bycatch $ha^{-1}$ than those spread by the conventional flat–rectangular and batwing (FDR, $P < 0.05$; Table 1, Fig. 4c).

The only other catches significantly affected by otter-board configuration were the total system weight of retained eastern blue-spotted flathead, *Platycephalus caeruleopunctatus* (McCulloch) (33.0–49.5 cm TL), and the numbers and weights of retained leatherjacket, *Nelusetta ayraudi* (Quoy & Gaimard) (27.0–43.5 cm TL), and discarded spiky flathead, *Ratabulus diversidens*

**Table 3.** Summaries of selected performance and environmental impact indicators for triple-rigged trawls spread by either the conventional flat–rectangular, restrained flat–rectangular or batwing otter boards. Where appropriate, the predicted means (± SE) from linear mixed models are provided and were calculated with centred significant continuous covariates. Spread ratio was calculated as total wing-end spread ÷ total headline length

| Variable | Conventional flat–rectangular | Restrained flat–rectangular | Batwing |
|---|---|---|---|
| Total wind-end spread (m) | 29.43 ± 0.18[A] | 28.43 ± 0.15[B] | 26.17 ± 0.18[C] |
| Total spread ratio | 0.77 | 0.71 | 0.68 |
| Speed over the ground ($m\ s^{-1}$) | 1.16 ± 0.18[B] | 1.22 ± 0.02[A] | 1.26 ± 0.02[A] |
| Area trawled (ha) | 25.03 ± 0.60[A] | 24.44 ± 0.60[A] | 22.55 ± 0.60[B] |
| Otter-board angle of attack (°) | 40.18 ± 0.36 | 22.74 ± 0.65 | 20.00 ± 0.00 |
| Total otter-board bottom contact (m) | 2.58 ± 0.02 | 1.54 ± 0.02 | 0.30 ± 0.00 |
| Drag (kgf) | 1341.28 ± 16.00[A] | 1361.37 ± 13.84[A] | 1267.80 ± 15.79[B] |
| Fuel | | | |
| $L\ h^{-1}$ | 29.90 ± 0.79[A] | 31.33 ± 0.70[A] | 29.29 ± 0.79[A] |
| $L\ ha^{-1}$ | 2.40 ± 0.09[A] | 2.52 ± 0.07[A] | 2.56 ± 0.08[A] |

Dissimilar superscript letters indicate significant differences detected in false-discovery-rate pairwise comparisons ($P < 0.05$).

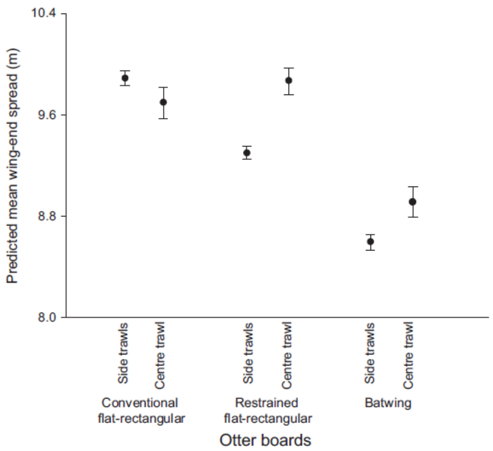


**Figure 3.** Differences in predicted mean ± SE wing-end spreads of the side and centre trawls for each otter-board configuration.

(McCulloch) ha$^{-1}$ trawled (8.5–24.0 cm TL; LMM, $P < 0.05$; Table 1, Fig. 5). While FDRs did not separate the means, the trawls spread by the conventional flat–rectangular otter boards retained considerably fewer of the above species ha$^{-1}$ (by 50–86%) than those spread by the other two otter board configurations (Fig. 5a–c).

## Discussion

This study quantified the concomitant effects of modifying otter-board design (or configuration) on the engineering and catching performances of triple-rigged penaeid trawls and, in doing so, contributes towards a growing body of recent efforts at refining general trawl spreading mechanisms to reduce their environmental impacts (Sala *et al.* 2009; Sterling & Eayrs 2010; Broadhurst *et al.* 2012, 2013a,b; Suuronen *et al.* 2012; McHugh *et al.* 2015a,b,c). Prior to discussing the various effects of otter board configuration on system performance and the implications for future refinements, the overall engineering consistency of the three triple rigs warrants mention.

The three configurations behaved similarly in terms of the measured technical variables affecting their total spread, with positive and negative relationship between the depth fished and SOG, respectively. These observations support those from previous studies and can be explained by the corresponding influences of hydrodynamic forces (e.g. Weinberg *et al.* 2002; Weinberg & Kotwicki 2008). Specifically, as depth increases, triple rig has the unique characteristic where the divergence angle of the warp reduces and this allows the spread to increase. This same effect has been observed for fish trawls (Weinberg & Kotwicki 2008), but is not a feature of more popular penaeid-trawl systems such as double- or quad-rigs. Also, at slower SOG (or with assisted current), there would be less drag created by the gear, allowing it to be spread wider by the otter boards (Weinberg *et al.* 2002) because they would have greater seabed contact pressure and therefore more ground shear.

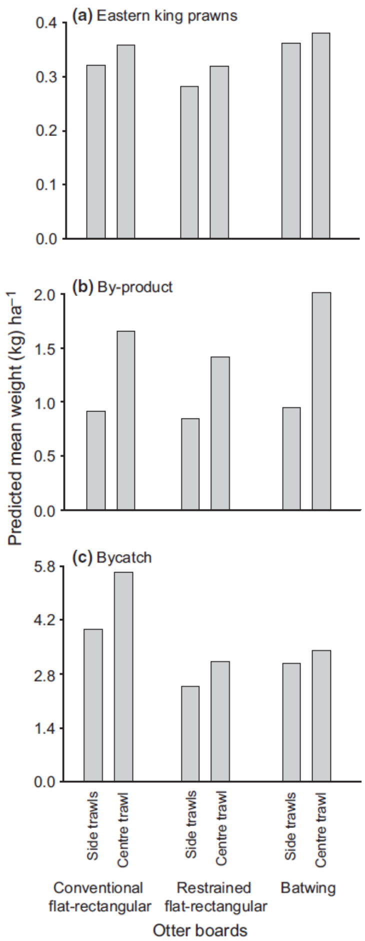


**Figure 4.** Differences in predicted mean weights ha$^{-1}$ trawled of (a) eastern king prawns, *Penaeus plebejus*, (b) by-product and (c) bycatch between the side (port and starboard combined) and centre trawls for each otter-board configuration.

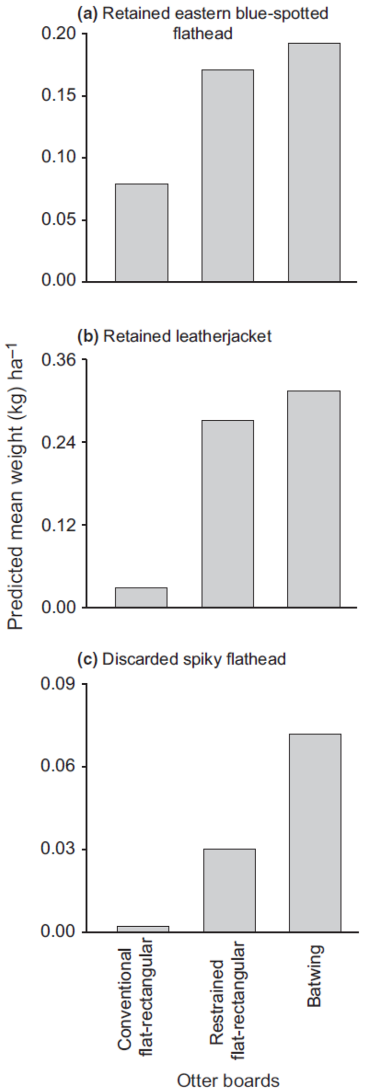


**Figure 5.** Differences in predicted mean weights $ha^{-1}$ trawled of (a) retained eastern blue-spotted flathead, *Platycephalus caeruleopunctatus*, (b) retained leatherjacket, *Nelusetta ayraudi*, and (c) discarded spiky flathead, *Ratabulus diversidens,* pooled across the three trawls (i.e. total system) within each otter-board configuration.

Notwithstanding consistency in performance across depths and towing speeds, there were significant differences among otter-board configurations in their evoked wing-end spreads. The batwing otter board has been designed to maintain spreading force with less drag than conventional otter boards, while substantially reducing bottom contact (by >85%) – which, in this study, corresponded to 2.28-m less lateral contact than the conventional flat–rectangular design, or ~2 ha over a two-hour deployment (assuming an average SOG of 1.2 m $s^{-1}$) and therefore up to ~8 ha per night (assuming eight hours trawling). However, the surface area of the tested batwings was not sufficient to maintain similar SRs as the conventional flat–rectangular design. Further, although the batwings had less drag (by ~5%), at least some of these differences can be attributed to the reduced trawl SR (and therefore shallower angle of netting to the tow direction; Broadhurst *et al.* 2014).

The drag similarities were somewhat anticipated, because beyond being towed slightly faster, the greatest drag reductions by the batwing should occur in those systems spread just by paired otter boards (e.g. single- and double-rigs) and without sleds (quad-, dual- and triple-rigs), which reduce the contribution of the spreading mechanism to overall system drag (Broadhurst *et al.* 2013a,b; McHugh *et al.* 2015a). Nevertheless, because of the unique design of the batwing, simply increasing the sail area would enable trawl wing-end spread to be increased to that provided by the conventional flat–rectangular otter boards, while maintaining similar drag (and fuel rates and intensities), but still with the same low bottom contact. Based on recent work by McHugh *et al.* (2015c), such an outcome should evoke concomitantly fewer habitat disturbances.

Restraining the flat–rectangular otter boards also failed to reduce drag, although like for the batwing there was a reduction in their lateral contact, which compared to the conventional configuration would manifest as ~0.9 ha less contact over a two-hour deployment (~3.6 ha per vessel per night). Restraining the flat–rectangular otter boards still provided sufficient force to spread the entire system, because there was no significant difference in the centre-trawl wing-end spreads between the retained and unrestrained configurations. It is possible that the restraining line contributed towards drag and therefore affected the spread of the outside trawls; an effect that could be reduced by using thinner dyneema material (but possibly with some cost to bycatch reduction – see below).

In addition to reducing bottom contact, the restrained flat–rectangular and batwing otter boards positively affected species selection. Specifically, both new configurations maintained standardised catches of eastern king prawns at the same rate as the conventional flat–rectangular otter boards. Further, because there were no significant differences in fuel rates or intensities, there were no absolute catch losses. However, compared with all other trawls and configurations, the side trawls spread by the restrained flat–rectangular otter boards caught significantly less bycatch (by up to 37%, and mostly comprising small teleosts).

The apparent lower bycatches in the restrained flat–rectangular side trawls may reflect the utility of the line as a BRD (McHugh *et al.* 2014). For example, McHugh *et al.* (2014, 2015b) showed that attaching lines between the towing points of paired otter boards in a single rig (deployed during daylight) reduced the total bycatch weight by up to 52%, with the results positively correlated with the surface area (and potentially visual stimulus) of line attachments (plastic strips or canvas panels). It might be possible, therefore, to increase the escape of small fish from the triple-rigged trawls examined here, simply by increasing the surface area of the retaining line (and/or adding illumination to improve contrast), although any concomitant effects on drag might need to be offset by a greater otter board surface area.

The restraining line did not concomitantly affect by-product. A possible hypothesis for such a result is that the by-product comprised a large proportion of invertebrates [octopus, *Octopus* sp, cuttlefish, *Sepia* spp., and smooth bugs, *Ibacus chacei* (Brown & Holthuis)], which may have more limited responses to trawls during capture than teleosts (e.g. Scandol *et al.* 2006), as well as larger benthic teleosts, such as flatheads, the orientation of which (i.e. on the seabed) might have precluded them detecting the restraining line. It is apparent, however, that the latter species were affected by other changes associated with the modified otter boards. In particular, the trawls spread by the batwing and restrained flat–rectangular otter boards caught significantly greater numbers of retained eastern blue-spotted flathead and leatherjacket and discarded spiky flathead. Such impacts were unlikely due to any confounding impacts of slightly different SRs (and therefore netting-panel angles and contact probabilities), given that there were no effects on other catches, including eastern king prawns or smaller individuals of bycatch (Broadhurst *et al.* 2014).

One possible hypothesis to explain the increase in catches of the three benthic species above is the more consistent otter-board angle in relation to wing angle; that is, both low AOA otter boards would have approached the wing angle more closely that the conventional flat–rectangular. A less abrupt angle might be better for herding some fish – especially larger (retained) ones – into the trawls and perhaps more towards the centre trawl, given the consistently greater catches of total by-product in this net. Such species-specific responses to trawls are common (Broadhurst *et al.* 2006), although additional research is required to investigate these observations, and also why the centre trawls consistently caught more eastern king prawns $ha^{-1}$, irrespective of otter-board configuration.

The results from this study show that it is possible to considerably reduce otter-board AOA and therefore bottom contact (e.g. up to 8 ha of contact per vessel per night) and (where relevant) associated concerns regarding habitat impacts (Caddy 1973; Kaiser *et al.* 2002), while maintaining the desired catches in triple-rigged penaeid trawls. Ideally, to promote adoption and ongoing industry development, such modifications should also have good engineering benefits (i.e. lower drag, and fuel rates and intensities). In this regard, the batwing has clear utility for single- and double-rigs and with comparable purchase costs and maintenance as flat–rectangular otter boards (discussed by McHugh *et al.* 2015a). Nevertheless, more research is required to assess designs that provide the same efficiency improvements for triple rigs. The energy intensity of penaeid trawling combined with increasing costs of fossil fuels means that such work should be given priority along with ongoing attempts at improving size and species selectivity (Suuronen *et al.* 2012).

## Acknowledgments

This study was funded by the New South Wales (NSW) Department of Primary Industries and the Australian Fisheries Research and Development Corporation (FRDC; Grant No. 2011/010). Funding for developing and implementing the batwing otter board was provided by the World Wildlife Fund (PA 01, PA 17; Envirofund 62463) and the FRDC (Grant nos 2004/060, 2008/079). Thanks are extended to the (NSW) Professional Fishing Association, Donald Anderson, Graeme Williams, Liz Hanna and especially Craig Brand.

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**Appendix 10.** McHugh, M., Broadhurst, M. K., Sterling, D.J., Skilleter, G.A., Millar, R.B. and Kennelly, S.J. 2015. Relative benthic disturbances of conventional and novel otter boards. ICES J Mar Sci. 72: 2450–2456.

ICES Journal of Marine Science Advance Access published June 1, 2015

ICES Journal of Marine Science

ICES CIEM International Council for the Exploration of the Sea Conseil International pour l'Exploration de la Mer

ICES Journal of Marine Science; doi:10.1093/icesjms/fsv100

# Relative benthic disturbances of conventional and novel otter boards

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McHugh, M. J., Broadhurst, M. K., Sterling, D. J., Millar, R. B., Skilleter, G., and Kennelly, S. J. Relative benthic disturbances of conventional and novel otter boards. – ICES Journal of Marine Science, doi: 10.1093/icesjms/fsv100.

Received 26 February 2015; revised 1 May 2015; accepted 11 May 2015.

Reducing otter-board angle of attack (AOA) has been proposed as a way to limit the habitat impacts of demersal trawls, but there are few quantitative assessments. This study tested the hypothesis that a novel otter-board design, termed the "batwing" (comprising a 0.1-m wide sled with an offset sail at 20° AOA) would have relatively fewer bottom impacts than a conventional flat-rectangular otter board (35° AOA, with a similar hydrodynamic spreading force). Pairs of each otter board were suspended beneath a purpose-built rig comprising a beam and posterior semi-pelagic collection net and repeatedly deployed across established trawl grounds in an Australian estuary. Compared with the conventional otter boards, the batwings displaced significantly fewer empty shells (*Anadara trapezia* and *Spisula trigonella*) by 89% and school prawns (*Metapenaeus macleayi*) by up to 78%. These rates were similar to the difference in base-plate bottom contact (87%). Further, the batwing damaged proportionally fewer damaged shells, attributed to their displacement away from the board's surface area. Other debris (lighter pieces of wood) and benthic fish (bridled gobies, *Arenigobius bifrenatus*) were not as greatly mobilised (i.e. reduced by 50 and 25%, respectively); possibly due to their position on or slightly off the bottom, and a similar influence of hydrodynamic displacement by the hydro-vane surface areas. Although the consequences of reducing otter-board bottom contact largely remain unknown, low AOA designs like the batwing may represent a practical option for fisheries where trawling is perceived to be hazardous to sensitive habitats.

**Keywords:** batwing, habitats, hydrodynamic drag, impact, otter boards.



## Introduction

Demersal trawling occurs throughout the world's oceans and is believed to have originated in the mid-14th century with a design called the "wondyrchoum"; essentially a precursor to modern beam trawls (Robinson, 1996; Kennelly and Broadhurst, 2002). Technology evolved to "otter trawling" in the late 19th century, which involves the nets being horizontally spread by the relative flow of water (from forward motion of the gear) acting on hydro vanes (or "otter boards"; Jones, 1992; Auster and Langton, 1999). Since the early 20th century, otter trawling has become established as the world's most widely used mobile fishing gear and is considered a principal source of anthropogenic disturbances to benthic habitats (Jones, 1992; Auster and Langton, 1999; Collie *et al.*, 2000; Kaiser *et al.*, 2002).

Many concerns about habitat impacts associated with demersal otter trawls have focused on the otter boards, which leave discernible marks on the substratum, and, in some cases, lead to unwanted ecosystem impacts (Dayton *et al.*, 1995; Auster and Langton, 1999; Kaiser *et al.*, 2002). Substrate type (e.g. hard or soft) and its mobility will dictate the impact of otter boards and recovery times, whereby soft sediments (e.g. mud and sandy-mud) with a low level of natural disturbance, will be most affected and take longer to recover than harder substrata (e.g. sand) (DeAlteris *et al.*, 1999, 2000; Dernie *et al.*, 2003).

Although otter-board impacts are a direct function of their weight and contact pressure (by necessity they have the greatest concentrated mass within demersal trawls), there are two other key factors that ultimately affect the substrate contact area. First is the height-to-length ratio, or aspect ratio of the foil, which determines the otter board's length for a given foil surface area (Patterson and Watts, 1985; Seafish *et al.*, 1993). Second is the operational angle of attack (AOA), which typically is between 30 and 45° (Patterson and Watts, 1985; Seafish *et al.*, 1993). Considering these two factors, an otter board's lateral span of seabed contact can be deduced from simple trigonometry to be the base-plate width, for an AOA of 0°, to a maximum of the base-plate length, for a hypothetical 90° AOA.

Many conventional demersal otter boards are flat and rectangular with a low aspect ratio to match their high AOA (>35°), which, although not required to adequately spread the trawls during fishing (i.e. 30° is most effective, whereas ~20° is the most efficient), ensures their stability during deployment (Sterling and Eayrs, 2010). A novel, high-aspect, otter-board design that achieves a consistent low AOA and has good stability is the "batwing" (Sterling and Eayrs, 2008; McHugh *et al.*, 2015). The batwing foil—comprising a polyurethane (PU) sail set on a stainless-steel boom and mast—acts like an independent kite with a single longitudinal connection to the trawl system via a heavy main sled made from mild and stainless steel. The batwing is configured so that the sled base-plate aligns to the tow direction, whereas the sail has a consistent AOA (20°) and rides on a PU "flap" that passes lightly over the seabed on a layer of high-pressure water for most of its length. Conceivably, because the batwing mostly contacts the seabed via its base-plate width (assuming the sail has minimal contact), it should evoke proportionally fewer habitat disturbances than conventional, low-aspect, and high AOA otter boards.

Identifying component-specific effects on habitats are difficult when using a complete trawl configuration (i.e. otter boards, net, ground gear, and associated gear; Gilkinson *et al.*, 1998). One method is via *in situ* observations (e.g. video and sonar imaging), although in some fisheries these are limited owing to low visibility and difficulties discerning trawl-mark longevity (existing or new; Smith *et al.*, 2007). Furthermore, proper experimental procedures require observations (e.g. video and sonar) to be collected before, during, and after planned experiments (Schwinghamer *et al.*, 1998), which can be a difficult task in established fisheries (Dayton *et al.*, 1995).

An alternative option involves assessing broad relative benthic disturbances among different otter boards in the same space and time, which can then be used as a proxy for determining the utility or otherwise of modified designs for conserving habitats. We follow this approach here using a purpose-built test rig comprising a posteriorly located collection net (analogous to a covered codend) to investigate the hypothesis of no differences in the relative substrate disturbances of conventional flat-rectangular and batwing otter boards. The rig was alternately deployed across flat (sandy-mud), previously trawled areas known to contain large areas of empty shell (*Anadara trapezia* and *Spisula trigonella*) and other macro-debris, so that their abundances in the collection net and any inflicted damage could be used as relative indices of disturbance.

## Material and methods

The experiment was completed in Lake Wooloweyah (29°26′S 153°22′E; ~1–2 m depth), New South Wales, Australia, during the Austral autumn, 2014, using a 10-m penaeid trawler (104 kw) configured with two independent hydraulic winches to tow double rig. The trawler had a global positioning system (GPS; Lowrance, HDS5) to record speed over the ground (SOG in m s$^{-1}$) (every 60 s). The experiment was done at the end of the fishing season and with no other vessels present on the trawled area.

### Otter boards and the testing assembly

Two otter-board pairs were assessed; both with 0.1-m base plates (Figures 1 and 2). The first otter-board pair was termed the "flat-rectangular" and represented a standard design used nationally and internationally, comprising a mild-steel frame with marine-grade plywood inserts (52.53 kg, 1.39 × 0.61 m, solid area of 0.77 m$^2$; Figure 1a). The second pair was the "batwing"; each with a main sled made from mild and stainless steel, and a PU sail on a stainless-steel boom and mast (60.74 kg, 1.12 × 1.23 m, 0.74 m$^2$) at a 20° AOA (Figures 1b and 2a).

Both otter-board pairs were deployed, one pair at a time on a purpose-built test rig comprising a 6-m beam secured at each end to sleds (1.07 × 0.76 × 0.1 m); inside which a "collection net" (a design described by McHugh *et al.*, 2015, and made from 32- and 12-mm polyethylene and polyamide mesh in the body and codend, respectively) was posteriorly attached (Figure 2). The collection net had a 20-cm diameter float attached in the centre of its headline to maximise the vertical opening posterior to the otter boards, but no ground gear. Rather, the lower frame line was attached 0.1 m above and inside the sled base plates so that it could not contact (nor disturb) the substrate, nor collect any entrained material from the sled (Figure 2). We validated this lack of substrate contact in earlier work, when the configuration was fished without the attached otter boards (Broadhurst *et al.*, 2015).

The flat-rectangular and batwing otter boards were bolted at their conventional fishing orientations (35 and 0° base-plate AOA, providing total lateral bottom contacts of 1.60 and 0.20 m, respectively) to independent aluminium frames that could be secured immediately below the beam and 1-m either side of the centre line, so that the base plates were on the same plane as the sleds, and in front of the collection net (Figure 2). The beam assembly was attached via a 7-m bridle to the towing warps on one side of the vessel, and a conventional otter trawl was operated on the other side (to balance the vessel during towing).

Although the tip of the batwings extended slightly higher than the collection net, we did not consider that this would confound the estimates of collected debris. Logic for this statement is based on previous underwater video observations, which revealed that unlike flat-rectangular otter boards which disturb the substratum via the base-plate AOA and immediately create quite high sand and debris plumes, the 0° AOA of the batwing base plate and only slight contact of the sail foot on the seabed limits the posterior plume in the water column to the lower section (Sterling and Eayrs, 2008).

On each fishing day, an otter-board pair was suspended below the beam and deployed for 10 min along independent tracks (Figure 2). The otter-board pairs were alternately deployed among four days and also within 2 days, providing a total of 36 replicates of each.

### Data collected and statistical analyses

Data collected during each deployment were restricted to the test rig and collection net and included: the total distance (m) trawled

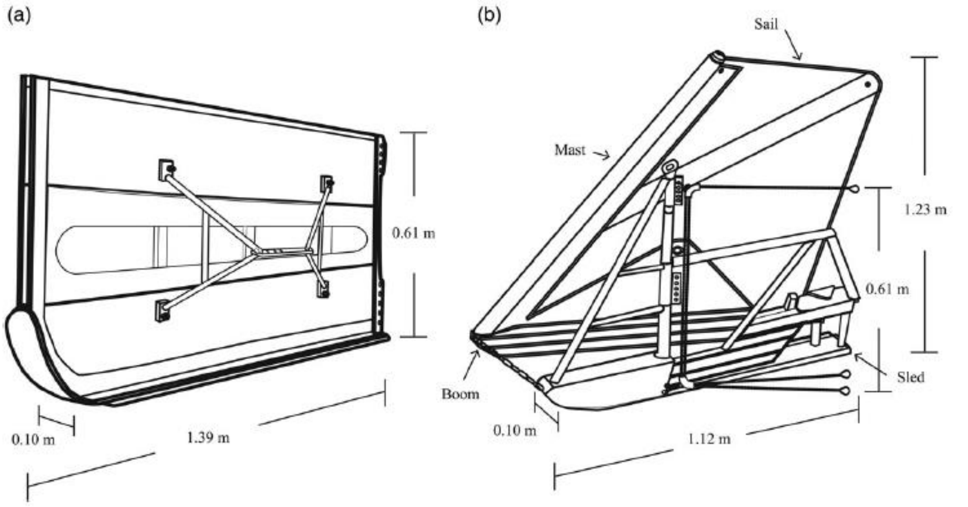


**Figure 1.** Three-dimensional representation of the (a) flat-rectangular (1.39 × 0.61 m; 52.53 kg) and (b) batwing otter boards (1.12 × 1.23 m; 60.74 kg) tested in the study.

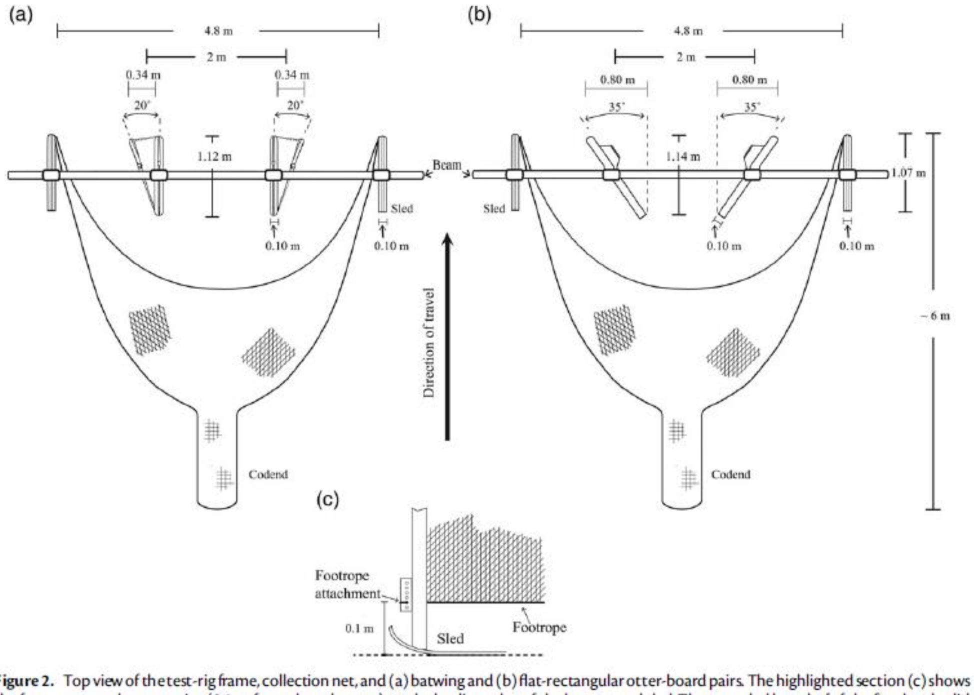


**Figure 2.** Top view of the test-rig frame, collection net, and (a) batwing and (b) flat-rectangular otter-board pairs. The highlighted section (c) shows the footrope attachment point (0.1 m from the substrate) on the leading edge of the beam-trawl sled. The recorded lengths [of the fixed and solid structures in (a) and (b)] are proportional, but owing to variable dynamics, the net shape and length were estimated.

(rig on and off the bottom—obtained from the GPS); SOG ($m\ s^{-1}$); total catch weight; the numbers and weights of individual fauna; sizes of key species (carapace length, CL, for prawns and total length, TL, for fish to the nearest 1 mm); and the weights of shells and other debris (mostly water-saturated wood). Estimates of faunal abundance were derived using a 500-g subsample of the total catch, processed in the laboratory. Empty shells were also classified as "damaged" (i.e. broken pieces) or "undamaged" (structurally complete). Owing to difficulties in identifying prawns to the species level, two groups were classified: individuals >5-mm CL (entirely school prawns, *Metapenaeus macleayi*) and those <5-mm CL (some school prawns, but mostly glass shrimp, *Acetes* spp.), termed "misc. Dendrobranchiata".

All data were separately analysed in linear mixed models (LMMs), with some standardised before analyses. Catch numbers and weights were analysed as log-transformed data, after being standardised to per 500-m deployment (because of differences in the distance towed—Results). All other data, including the mean CL of school prawns (>5-mm CL), ratio of damaged and undamaged shells, and deployment distance were analysed in their raw form.

All LMMs included "otter-board pair" as a fixed effect, whereas "days", "deployments", and, where relevant, their interaction were included as random terms. All models were fitted using ASReml (Gilmour *et al*., 2006) in the R software package (R Core Development Team, 2014). The null hypothesis of no difference between otter boards was tested using a Wald *F*-test, which is a modification of the standard Wald test to provide better inference about fixed effects in mixed models. Specifically, the Wald *F*-test is derived by dividing the standard Wald test statistic by the denominator degrees-of-freedom following Kenward and Roger (1997).

## Results

A total catch of 87.82 kg was retained in the collection net, comprising school prawns (3.97 kg), misc. Dendrobranchiata (6.29 kg), shells (50.28 kg), wooden debris (12.71 kg), blue blubber jellyfish, *Catostylus* spp. (9.71 kg), and teleosts (4.86 kg). The latter included 23 species, but five comprised 85% of the total (by number): southern herring, *Herklotsichthys castelnaui* (38%); pink-breasted siphonfish, *Siphamia roseigaster* (17%); whitebait, *Hyperlophus vittatus* (15%); Australian anchovy, *Engraulis australis* (11%); and bridled goby, *Arenigobius bifrenatus* (4%).

We attempted to tow the test rig with the batwing and flat-rectangular pairs at similar SOGs (ranging between 1.17 and 1.53 $m\ s^{-1}$) but, while comparable, the mean ± SE deployment distances (833 ± 4.17 and 821 ± 4.17 m) were significantly different (LMM, $p < 0.05$; Table 1). Consequently, all numbers and weights are discussed per standardised distance trawled (to 500 m for convenience). Based on the deployment distances, the mean total substrate contacts of the batwing and flat-rectangular pairs were 166.68 ± 0.98 and 1312.86 ± 5.26 $m^2$, respectively.

Compared with the flat-rectangular otter board's 500-m $deployment^{-1}$, the net behind the batwing pair had significantly lower: weights of total catch (predicted mean reduced by 80%), empty shells (by 89%) and debris (by 50%); numbers and weights of school prawns (by 78 and 72%); and numbers of bridled gobies (by 25%; LMM, $p < 0.05$; Figure 3a–e; Table 1). The batwing pair also damaged relatively fewer empty shells (28 ± 3.0 vs. 40 ± 3.0% of the total), but directed more (91%) whitebait 500 m

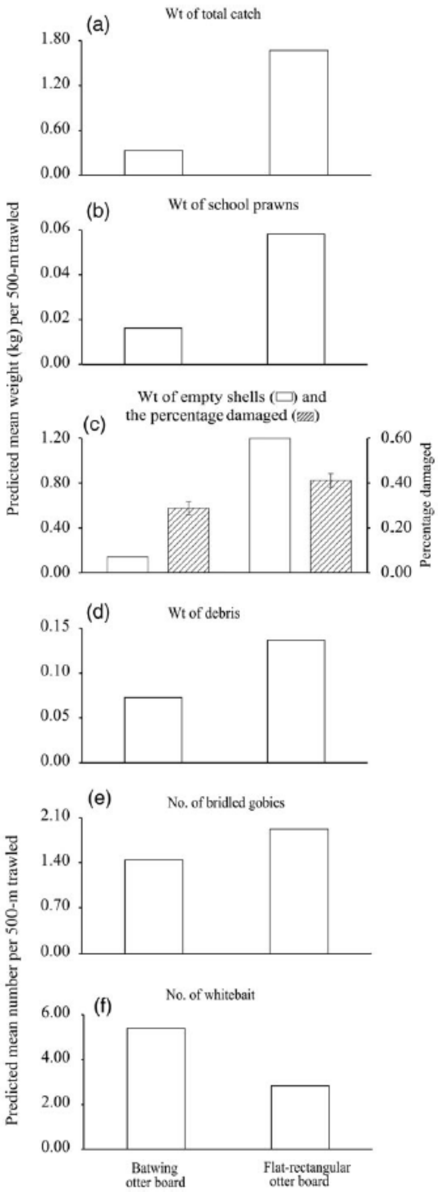


**Figure 3.** Significant differences in predicted mean catches in the collection net per 500 m deployment between the flat-rectangular and batwing otter-boards pairs for the weights of (a) total catch, (b) school prawns, *M. macleayi*, (c) empty shells (*A. trapezia* and *S. trigonella*, with the percentage damaged, ± SE), and (d) debris and the numbers of (e) bridled gobies, *A. bifrenatus*, and (f) whitebait, *H. vittatus*.

**Table 1.** Summaries of Wald *F*-values from LMMs assessing the importance of the fixed effect of otter-board pair (batwing vs. flat rectangular) in explaining variability among catches in the collection net.

| Variables | Wt (kg) | No. | Wald *F* |
|---|---|---|---|
| Deployment distance | – | – | 4.76* |
| Wt of total catch 500 $m^{-1}$ | 53.51 | – | 26.83*** |
| Wt of school prawns, *M. macleayi* 500 $m^{-1}$ | 2.42 | – | 21.56** |
| No. of school prawns 500 $m^{-1}$ | – | 4 794 | 13.32* |
| Wt of misc. Dendrobranchiata 500 $m^{-1}$ | 3.79 | – | 2.94 |
| No. of misc. Dendrobranchiata 500 $m^{-1}$ | – | 13 219 | 0.57 |
| Mean CL of school prawns >5 mm | – | – | 2.58 |
| Wt of empty shell 500 $m^{-1}$ | 30.93 | – | 27.61*** |
| Proportion of empty shell damaged | – | – | 11.5* |
| Wt of debris 500 $m^{-1}$ | 7.74 | – | 6.30* |
| Wt of total teleost bycatch 500 $m^{-1}$ | 2.95 | – | 0.47 |
| No. of whitebait, *H. vittatus* 500 $m^{-1}$ | – | 185 | 6.94* |
| No. of bridled goby, *A. bifrenatus* 500 $m^{-1}$ | – | 55 | 5.89* |
| No. of southern herring, *H. castelnaui* 500 $m^{-1}$ | – | 473 | 0.61 |
| No. of pink-breasted siphonfish, *S. roseigaster* 500 $m^{-1}$ | – | 211 | 0.05 |
| No. of Australian anchovy, *E. australis* 500 $m^{-1}$ | – | 140 | 0.05 |

Numbers and weights are presented in their raw form and before analyses were standardised to per 500-m trawled and then log-transformed. CL, carapace length; –, not relevant.
$^{*}p < 0.05$.
$^{**}p < 0.01$.
$^{***}p < 0.001$.

deployment$^{-1}$ into the collection net, than the flat-rectangular configuration (LMM, $p < 0.05$; Figure 3f; Table 1).

There was no significant difference in school prawn mean sizes (>5-mm CL) collected behind the batwing (10.31 ± 0.26 mm CL) or flat-rectangular (9.76 ± 0.26 mm CL) otter-board pairs (LMM, $p > 0.05$; Table 1). Although insufficient individuals were caught to enable analyses of mean TL among deployments, the pooled size frequencies of bridled gobies and whitebait were also similar between configurations (Figure 4). There were no other significant differences between treatments (LMM, $p > 0.05$; Table 1).

## Discussion

This study represents an innovative approach to describing the reductions in bottom contact and associated habitat disturbances that can be achieved via modifications to otter-board design. The observed relative differences in live catches and non-motile entrained material can be explained by behavioural responses and density-dependent mechanisms related to the substrate contact and AOA of the otter boards.

The results suggest efficiency differences between the flat-rectangular and batwing otter boards, but it should be noted that there was an experimental-design artefact which could confound the interpretation of some variables. Specifically, the otter boards were inside the collection-net wings and closer to the opening than typical trawl configurations. Further, the necessary width of the collection net (i.e. 4.8 m in total) would have meant some organisms were caught, irrespective of the otter boards. Nevertheless, the significant increase in numbers of whitebait, but fewer bridled gobies in the net behind the batwing may reflect its greater aspect ratio and lesser bottom contact. Specifically, whitebait is a schooling species that might have more easily avoided the net behind the flat-rectangular otter boards owing to their large projected area (a function of the 35° AOA) and the associated visual stimulus (e.g. greater sand clouds). In contrast, bridled gobies are benthic and therefore more likely to be affected by the reduced bottom contact of the batwing.

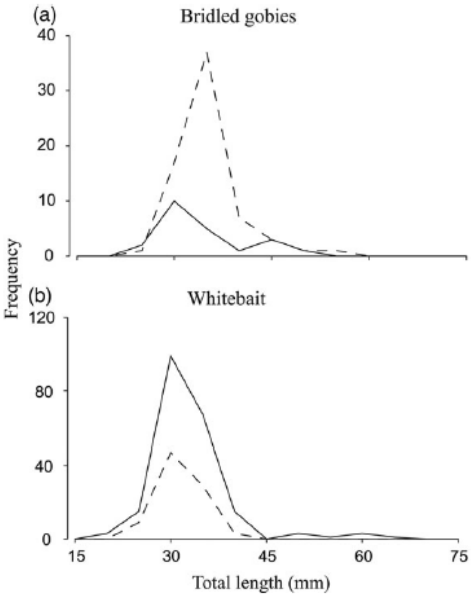


**Figure 4.** Size-frequency plots of (a) bridled gobies, *A. bifrenatus*, and (b) whitebait, *H. vittatus* in the collection net per absolute deployment for the flat-rectangular (dashed lines) and batwing (solid lines) otter-board pairs.

The observed differences in school prawn catches support the latter hypothesis, with relatively fewer in the net behind the batwing pair and at a rate (72–78%) almost proportional to the concomitant reduction in otter-board base-plate contact (87%). The same effects were hypothesised to account for significant differences in school prawn catches between beam (i.e. just sleds) and otter trawls previously tested in the same lake (Broadhurst *et al.*, 2012), but did not extend to the batwing when conventionally rigged to otter trawls (McHugh *et al.*, 2015). Such differences possibly reflect spatial or temporal variability in school-prawn behaviour in terms of their level of activity and catchability (emergence from the substrate). Dendrobranchiata catches were not similarly affected here, but the glass shrimp were probably dispersed higher in the water column. Further, the small size of glass shrimp would have precluded any sustained swimming ability (e.g. Daniel and Meyhofer, 1989) or active escape response.

The relationship between entrained material and base-plate contact was further supported by the non-motile catches, and especially shells. For example, the batwing pair displaced 89% fewer shells into the collection net than the flat rectangular, almost exactly the same as the reduction in base-plate contact (87%). Further, the batwing damaged proportionally fewer shells, which may reflect the mechanism of displacement. The flat-rectangular otter board would have displaced shells along the length of the base plate with its intense ploughing action and guided some of the shells into the collection net by contact with the timber-and-steel hydro vane. In contrast, the batwing would have displaced fewer shells with the ramped, leading edge of the base plate, with only some then contacting the PU sail.

Although physical contact is an important factor affecting the displacement of dense material/organisms, otter boards also mobilise sediment via their hydrodynamic action (Main and Sangster, 1981; O'Neill and Summerbell, 2011). For example, the amount of material entrained by an otter board can be related to its hydrodynamic drag (O'Neill and Summerbell, 2011), because this is a measure of the rate at which energy is imparted by the otter board to the otherwise stationary water. This effect—an otter board's AOA and resulting hydrodynamic drag—is evident from observations by Sterling and Eayrs (2008), where the water flow around a batwing's low AOA sail did not separate and entrained less material (predominantly near its base) than a conventionally rigged flat-rectangular otter board (from which plumes filled the immediately posterior water column).

The relative difference in lighter displaced debris (mostly wood) between designs (e.g. 50%) may reflect the difference in drag of the otter boards and the energy contained in the water turbulence surrounding them while they produce a spreading force. Specifically, perhaps while the hydrodynamic effects of both boards were not sufficient to displace shells from the sediment, it was nevertheless the key force behind the disturbance/mobilisation of less dense material (like wood) into the collection net, and the extent reflects the relative hydrodynamic drag of the boards.

The results present a useful comparison of habitat disturbance between two contrasting otter-board designs; however, it is important to consider that the consequences in terms of actual ecological impacts remain unknown. Further, the test rig precluded replicating some aspects of conventional operations, including variations in otter-board contact weight and orientation with respect to pitch (tilt) or roll (heel). Notwithstanding the limitations, we believe the method replicated commercially representative otter-board–seabed interactions and provided accurate relative indications of the characteristics of the two designs.

Considering the above, low AOA and high-aspect otter boards like the batwing clearly have the potential to displace less benthic material and for bivalves, at least, with considerably less physical damage. Further research is required to examine the ecological implications of such reductions in various trawling environments, but the principles developed here might offer practical solutions where trawling in sensitive areas is considered problematic. A concomitant benefit of the batwing design is reduced drag, which has the potential to make trawling more energy efficient (e.g. McHugh *et al.*, 2015).

## Acknowledgements

This study was funded by the New South Wales (NSW) Department of Primary Industries and the Australian Fisheries Research and Development Corporation (FRDC; Grant no. 2011/010). Funding for developing and implementing the batwing otter board was provided by the World Wildlife Fund PA 01, PA 17; Envirofund 62463; and the FRDC (Grant nos. 2004/060, and 2008/079). Thanks are extended to the (NSW) Professional Fishermen's Association, Steve Everson, Don Johnson, Matt Harrison, Shiori Naka, Jen Marshall, and especially Craig Brand.

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*Handling editor: Finbarr (Barry) O'Neill*

**Appendix 11.** McHugh, M.K., Broadhurst, M.K., Sterling, D.J. and Millar, R.B. 2015. A 'simple anterior fish excluder' (SAFE) for mitigating penaeid-trawl bycatch. PLOS One. 10(4): e0123124. doi:10.1371/journal.pone.0123124.

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RESEARCH ARTICLE

# A 'Simple Anterior Fish Excluder' (SAFE) for Mitigating Penaeid-Trawl Bycatch

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OPEN ACCESS

**Citation:** McHugh MJ, Broadhurst MK, Sterling DJ, Millar RB (2015) A 'Simple Anterior Fish Excluder' (SAFE) for Mitigating Penaeid-Trawl Bycatch. PLoS ONE 10(4): e0123124. doi:10.1371/journal.pone.0123124

**Academic Editor:** George Tserpes, Hellenic Centre for Marine Research, GREECE

**Received:** October 14, 2014

**Accepted:** February 24, 2015

**Published:** April 2, 2015



**Data Availability Statement:** All relevant data are within the paper and its Supporting Information files.

**Funding:** Sterling Trawl Gear Services provided support in the form of salaries for authors DS, but did not have any additional role in the study design, data collection and analysis, decision to publish, or preparation of the manuscript.

**Competing Interests:** The authors have no Competing Interests that declares an affiliation to Sterling Trawl Gear Services, relating to employment, consultancy, patents, products in development or marketed products etc. This does not alter the

## Abstract

Various plastic strips and sheets (termed 'simple anterior fish excluders'–SAFEs) were positioned across the openings of penaeid trawls in attempts at reducing the unwanted bycatches of small teleosts. Initially, three SAFEs (a single wire without, and with small and large plastic panels) were compared against a control (no SAFE) on paired beam trawls. All SAFEs maintained targeted *Metapenaeus macleayi* catches, while the largest plastic SAFE significantly reduced total bycatch by 51% and the numbers of *Pomatomus saltatrix*, *Mugil cephalus* and *Herklotsichthys castelnaui* by up to 58%. A redesigned SAFE ('continuous plastic') was subsequently tested (against a control) on paired otter trawls, significantly reducing total bycatch by 28% and *P. saltatrix* and *H. castelnaui* by up to 42%. The continuous-plastic SAFE also significantly reduced *M. macleayi* catches by ~7%, but this was explained by ~5% less wing-end spread, and could be simply negated through otter-board refinement. Further work is required to refine the tested SAFEs, and to quantify species-specific escape mechanisms. Nevertheless, the SAFE concept might represent an effective approach for improving penaeid-trawl selectivity.

## Introduction

The capture and mortality of unwanted organisms (termed 'bycatch') by mobile demersal fishing gears is a global issue affecting many fisheries [1]. This is especially the case for penaeid trawling, which despite contributing only ~1.5% towards the total global marine wild harvest (estimated at a plateau of ~80 m t since 1985 [2]), accounts for >25% of all discarded bycatch (~7.3 m t per annum [1]); typically comprising small teleosts (<20 cm total length–TL), crustaceans and cephalopods [1, 3]. Historically, the mortality of such discards has raised widespread concerns, and primarily because of the potential for deleterious impacts on subsequent stocks [4, 5].

Considerable research has been done to mitigate penaeid-trawl bycatch and associated mortalities [6, 7]. Beyond temporal and spatial closures [7] the greatest efforts have focussed on retrospectively fitting 'bycatch reduction devices' (BRDs) to existing trawls. Broadly, such BRDs can authors' adherence to PLOS ONE policies on sharing data and materials.

be separated into two categories according to their principle separating function: those that rely on species-specific differences in size (termed 'mechanical-type BRDs'; e.g. the 'Nordmøre-grid'); or behaviour ('behavioural-type BRDs'; e.g. strategic 'square-mesh panels') to either actively or passively separate catches [6].

Notwithstanding their different classifications, the majority of BRDs are located in the posterior trawl (i.e. codend) and compared to conventional configurations can maintain penaeid catches within a ~10% loss, while reducing unwanted bycatches by ~30–70% [6]. Such results are positive, although there remains very little information on the mortality of organisms escaping BRDs (and therefore their ultimate benefit); primarily because accurate assessments are difficult, if not impossible, for many fisheries [8, 9]. However, because BRDs that facilitate the rapid escape of organisms with minimal physical contact (e.g. behavioural-type designs) should evoke low mortalities, an even more appropriate concept might be to anteriorly locate designs, and so promote complete trawl avoidance.

While the widespread use of such anterior BRDs is relatively uncommon, there have been successful attempts at demonstrating their utility [10]. For example, Seidel and Watson [10] designed a 'fish barrier', comprising mesh webbing across the trawl mouth that precluded the entry of large organisms, and used electrical stimulation to force penaeids up through an open benthic panel, and into the trawl. However, while this configuration had great potential, subsequently cheaper and more easily adaptable (to existing trawl codends) BRDs might have contributed towards its lack of commercial uptake. Also, some mesh-barrier designs (e.g. seal mitigation devices; [11]), placed at the trawl mouth can clog (e.g. with seaweed), which could either prevent penaeids entering or, alternatively, reduce wing-end spread and the area trawled [12].

The latter issue raises an important consideration. It is well established that complex BRDs are much less likely to be adopted and/or used correctly than those that are inexpensive and/or simple to maintain and operate [6]. Consequently, in terms of reducing unaccounted fishing mortality, the wide-scale use of simple and even marginally effective BRDs ultimately will have greater benefits than the limited use of far more effective designs. Given the above, an alternative to completely physically obstructing the trawl mouth may be to insert a behavioural-type BRD, which although being the less effective category of BRDs [6] should be smaller and less likely to affect trawl performance. While the concept of anterior behavioural-type BRDs is not new (e.g. [12–14]), the difficulty remains in focusing on the stimuli (e.g. visual or auditory) that will elicit the greatest response among non-target individuals without impacting on target species [15].

Irrespective of the BRD location (anterior or posterior) or type (behavioural or mechanical), during development there always should be an emphasis on hypotheses testing within a strong empirical experimental design [16]. To maximise penaeid catches while minimizing bycatch, any modifications should be clearly identified through systematic testing within the full range of possibilities [17, 18]. Methodically assessing modifications will facilitate further testing, acceptance or reassessment if the desired result is not achieved [17].

During a recent study in an Australian penaeid-trawl fishery, we tested an anteriorly located BRD that met some of the technical criteria discussed above [14]. Termed the 'simple anterior fish excluder' (SAFE), the design comprised a wire between beam-trawl sleds, from which 200- × 60- × 1-mm plastic strips were hung on universal swivels (allowing spinning). Compared to the control, the trawl with the SAFE reduced the catches of one species, southern herring, *Herklotsichthys castelnaui* by 48%, with minimal effect on catches of the targeted school prawns, *Metapenaeus macleayi*.

Here, we expand on the SAFE concept by first assessing the limits of practicality and effectiveness (including the original SAFE tested by McHugh et al. [14]) within a beam-trawl configuration before using this information to develop a prototype for testing on a more dynamic (i.e. non-rigid spreading mechanism) otter trawl. Specifically, our aims were to (i) test the hypothesis of no differences in the effectiveness of the SAFE area (i.e. 1, 3 and 11% of the two-dimensional opening) on the beam trawl and then, using this information, (ii) design and test an appropriate SAFE for use in otter trawling. The work was done in Australia, but the results have broader implications among other national and international crustacean-trawl fisheries.

## Material and Methods

### Ethics statement

The research was done in Lake Wooloweyah (29°26′ S 153°22′ E) New South Wales (NSW) Australia and in accord with the Department of Primary Industries scientific collection permit (No. P01/0059(A)-2.0). No specific permissions were required for access to Lake Wooloweyah. This study did not involve endangered or protected species, and all fish were returned to the water as soon as practicable, following each trawl deployment. Animal ethics approval for the research was granted by the NSW DPI Animal Care and Ethics Committee (Ref. 08/06). This study complied with all relevant regulations pertaining to the conservation of the surrounding environment and nearby wildlife, as detailed in the scientific collection permit.

### Location and vessel

Two experiments were completed in the Lake (sand and mud substrata ~1–2 m depth) during the Austral summer, 2013 on-board a 10-m double-rigged penaeid trawler (104 kw). The trawler had a global positioning system (Lowrance, HDS5) and two independent sum logs (model: Bronze + Log) to record speed over the ground (SOG) and through the water (STW; both in m $s^{-1}$). Load cells (Amalgamated Instrument Company; model no. PA6139) were configured so that they could be attached to bridles (always deployed to 12 m from paired winches) to measure the combined tension (kgf). The wing-end spreads of relevant otter trawls were obtained using Notus paired wireless sensors (see below). Data from the Notus sensors were received through an omnidirectional hydrophone and logged onto a laptop. All electronic data were recorded every 60 s.

### Experiment 1: testing three different SAFEs on a beam trawl

For the first experiment, the trawler was rigged with identical, paired 6-m beam-and-sled (1.07 × 0.76 × 0.1 m; 108 kg) assemblies. These spreading mechanisms were anteriorly attached to the towing wires via a 7.3 m bridle (Fig 1a) and posteriorly to trawl bodies with 9.19 m headlines (and footropes) and constructed from nominal 41-mm mesh (stretched mesh opening–SMO) and 1.25-mm diameter–Ø twisted polyethylene (PE) twine (for a trawl plan, see [14]). Both trawl bodies had identical conventional Nordmøre-grids (28-mm bar spacing) and square-mesh codends (120 × 75 bars) made from nominal 27 mm SMO polyamide mesh (1.25-mm Ø twine) hung on the bar (Fig 1b).

Three SAFE treatments were constructed; all stretched between the sleds at 0.3 above the baseplates (Fig 1a). The first treatment comprised a single 6-m long, 1.50-mm Ø stainless-steel wire (termed 'single wire') while the second and third had the same wires, but also included 12 evenly distributed flat strips (all 0.2 m long) of 1-mm thick green polypropylene (PP) that were either 0.06- (termed 'small plastic' and the same as those tested by McHugh et al. [14]) or 0.2-m ('large plastic') wide (Fig 1a). The PP strips were secured to the main line by a snap-lock (ball bearing) swivel that was attached midway along their leading edges (Fig 1a). Prior to the experiment, the small- and large-plastic strips were secured at several (e.g. centre, edge and middle) attachment points to a pole, which was pulled through the water (at ~1.50 m $s^{-1}$)

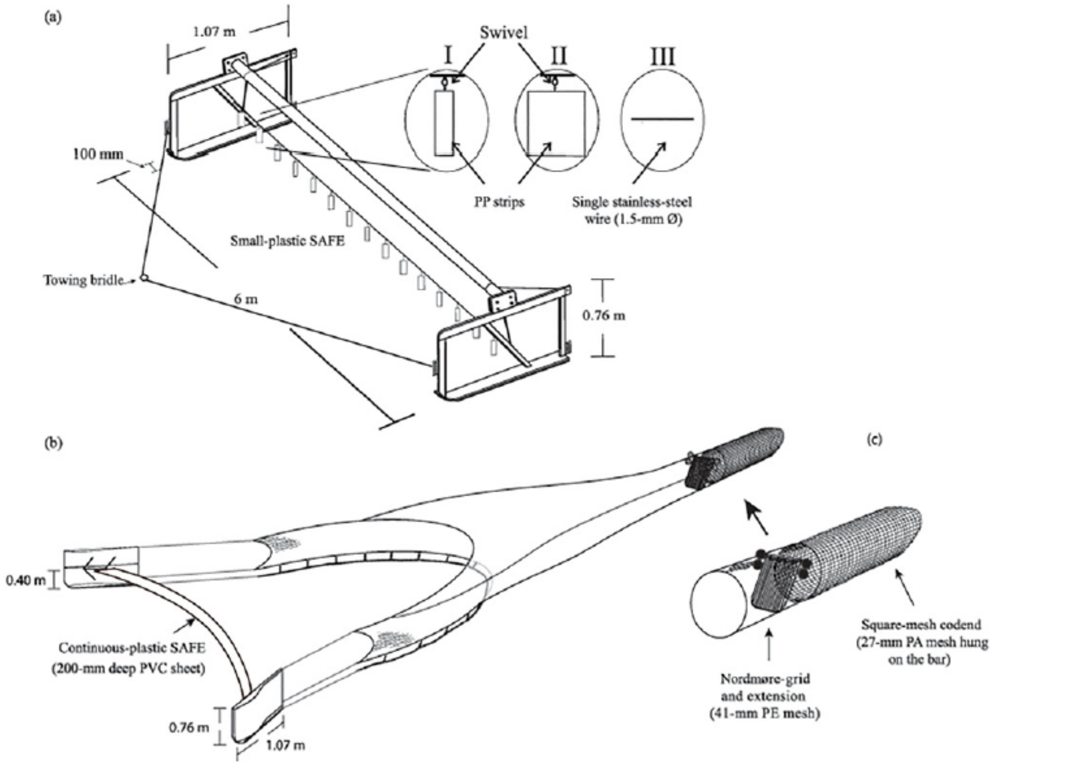


**Fig 1.** Schematic representation of the (a) beam trawl showing towing bridle and attachment locations of the (I) small-plastic (polypropylene–PP) (60 × 200 × 1 mm), (II) large-plastic (PP) (200 × 200 × 1 mm) and (III) the single-wire (1.50-mm Ø stainless steel) simple anterior fish excluders (SAFEs) tested in experiment 1 and (b) otter trawl with the polyvinyl chloride (PVC) continuous-plastic SAFE tested in experiment 2. The extension (with Nordmøre-grid) and codend (c), used in both experiments, are highlighted. PA, polyamide; PE, polyethylene.

doi:10.1371/journal.pone.0123124.g001

alongside a wharf and filmed with a Hero 3$^{+}$ GoPro. The plastic strips attached at the centre of their leading edges were observed to spin erratically.

On each fishing day, the paired beams were configured as either the control (i.e. no wire), or with one of the three SAFE treatments and deployed for 40 min. The control and SAFE treatments were then alternated, so that we completed one paired comparison of all four configurations on each day (i.e. six daily deployments). The two trawls were also swapped from side-to-side after the first three deployments, while the load cells were daily rotated from side-to-side. Over seven days, we completed 21 replicate deployments of each SAFE and the control.

## Experiment 2: testing a SAFE on an otter trawl

During the second experiment, the beam trawls were replaced with otter trawls, and the towing wires attached directly to paired cambered otter boards (1.07 × 0.76 m each and a total weight of 108 kg; Fig 1b). Sweep wires (2.89-m) were secured posterior to the otter boards and to 7.35-m headline length trawls that were constructed from the same materials and designs as those in experiment 1 and configured with the exact same Nordmøre-grids and codends (Fig 1b; for a trawl plan see McHugh et al. [14]).

A single SAFE treatment was constructed for use with the otter trawls. Termed the 'continuous-plastic', this design comprised a hemmed sheet of flexible white polyvinyl chloride (PVC) measuring 0.2 m wide (same as the green PP strips) × 6.4 m long, through which a 7.25-m (1.50-mm Ø) stainless-steel wire was threaded and terminated in snap clips (Fig 1b). The length of the wire was calculated based on an average wing-end spread during previous testing of the two trawls, and this was extrapolated to derive the otter-board spread [14]. The continuous-plastic SAFE was attached between the otter-board towing points at 0.40 m above the base-plates, so that it extended across the front of the trawl (Fig 1b).

At the start of each fishing day, the Notus paired sensors were attached to the wing ends of the trawls on each side of the vessel. The continuous-plastic SAFE was alternately and randomly clipped in front of one trawl, with both then deployed for 40-min up to six times each day. After three deployments, the trawls were swapped from side-to-side, while the load cells and paired Notus sensors were similarity rotated each day. Over five days, we completed 26 replicate deployments of the control and continuous-plastic SAFE.

## Data collected and statistical analyses

All trawl bodies and codends were checked for mesh uniformity by measuring 15 replicate SMOs using a local, purpose-built gauge. Other technical data collected during each deployment in each experiment included the: (i) warp tension (kgf) for each configuration; (ii) the total distance (m) trawled (sleds on and off the bottom—obtained from the GPS); and (iii) SOG and STW (m $s^{-1}$) (S1 and S2 Tables). Additionally, in experiment 2, data for wing-spread (m) were collected for each deployment (S2 Table).

Biological data collected at the end of each deployment included the: total weights of the targeted *M. macleayi* and bycatch; numbers of each bycatch species; and total lengths (TL to the nearest 0.5 cm) of the most abundant teleosts. Random samples of ~500 g of *M. macleayi* were bagged and transferred to the laboratory, where they were measured (carapace length—CL in mm), weighed and counted. These latter data were used to estimate the total numbers and the mean CLs caught during each deployment.

The hypothesis of no differences in the mesh sizes within the four trawl bodies, and two extensions and codends was tested in a linear model (LM). Within each experiment, the remaining data were analysed in linear mixed models (LMMs), with some standardised prior to analyses. The numbers and weights of catches were analysed per 40-min deployment and also per ha trawled (calculated using the known beam- and observed otter-trawl wing-end distances and the distance trawled) and as log-transformed data so that predicted effects would be multiplicative. All other data, including the mean CL of *M. macleayi*, mean TL per deployment of sufficiently abundant teleosts (occurring in >95% of deployments), drag and area and distance trawled were analysed in their raw form.

All LMMs included 'anterior-trawl configuration' (i.e. SAFEs vs. controls) as a fixed effect, while 'trawls', 'sides', 'days' and deployments (within days) were included as random terms. For the LMM assessing drags, 'load cell' was included as an additional random term while additional fixed co-variates included 'SOG', 'STW' (with 'sum-log' as a random term) and 'flow' (calculated as the speed of the current in the direction of travel and defined as SOG–STW). The preferred models were chosen based on forward variable selection with a p-value of 0.05 required for an effect to enter the model. All models were fitted using either the lmer function from the lme4 package or ASReml in R 2.15.3 (The R Project for Statistical Computing; http://www.r-project.org/), with the significance of anterior-trawl configuration determined using a

Wald *F*-value. In experiment 1, any significant Wald *F*-values for anterior-trawl configuration were subsequently explored using the Benjamini-Hochberg-Yekutieli procedure to control the false discovery rate (FDR) for multiple pair-wise comparisons [19].

## Results

There were no significant differences in the SMO between trawl bodies (means ± SE of 41.25 ± 0.08 mm), extensions (41.40 ± 0.17 mm) or codends (27.35 ± 0.10 mm) (LM, $p>0.05$). Pooled across experiments, the trawls caught 1753 and 154 kg of *M. macleayi* and total bycatch (Table 1). The total bycatch included 29 species, but in experiment 1, tailor, *Pomatomus saltatrix* (5.5–18.5 cm T), bully mullet, *Mugil cephalus* (5.5–15.5 cm TL), silver biddy, *Gerres subfasciatus* (5.0–13 cm TL), Ramsey's perchlet, *Ambassis marianus* (3.5–10.5 cm TL), yellowfin bream, *Acanthopagrus australis* (4.0–23.5 cm TL), and southern herring, *H. castelnaui* (6.5–16.5 cm TL) comprised >85% of catches (Table 1). In experiment 2, *A. marianus* (5.0–13.5 cm TL), *P. saltatrix* (4.0–17 cm TL), *G. subfasciatus* (6.5–13.5 cm TL), *H. castelnaui* (5.5–15 cm TL), *A. australis* (5.0–25 cm TL), and tarwhine, *Rhabdosargus sarba* (5.5–11 cm TL) were most prevalent (>77%; Table 1). These seven species, along with *M. macleayi*, form the basis of the biological analyses.

### Experiment 1: testing three different SAFEs on a beam trawl

The four beam-trawl configurations were towed at similar SOGs and STWs (ranging from 1.23 to 1.28 m $s^{-1}$) covering predicted mean ± SE areas between 1.90 ± 0.02 and 1.95 ± 0.02 ha per 40-min deployment, which were not significantly different (LMM, $p>0.05$; Table 2). None of the SAFEs significantly affected drag (predicted means ± SE between 205.3 ± 2.2 and 208.2 ± 2.2 kg, LMM, $p>0.05$; Table 2). STW and SOG were both positively correlated with drag, but they were not statistically significant ($p>0.05$).

Because there were no significant differences in the areas trawled, the biological data provided the same interpretations irrespective of standardization (i.e. to per ha; Table 2). Consequently, for convenience (and beyond Table 2), only the catches per 40-min deployment in experiment 1 are discussed and presented.

The anterior-trawl configuration had no significant effects on the catches, nor mean CL of *M. macleayi* (13.86–14.26 mm; LMM, $p>0.05$), but did significantly influence the number and weight of total fish bycatch, and the numbers of *M. cephalus*, *H. castelnaui* and *P. saltatrix* (LMM, $p<0.01$; Table 2; Fig 2a–2g), but not the mean size of the latter (LMM, $p>0.05$; Table 2). The significant effects on bycatch broadly were positively correlated with SAFE surface area (Fig 2b, 2d and 2e–2g). Specifically, compared to the control and the single-wire SAFE, both the small- and large-plastic SAFEs significantly and incrementally reduced the weights (by up to 27 and 51%) and numbers (by up to 26 and 47%) of total fish bycatch (FDR, $p<0.05$; Table 2, Fig 2b and 2d). The beam trawl with the large-plastic SAFE also caught significantly fewer *P. saltatrix* and *M. cephalus* than all other configurations (by up to 43 and 58%) and *H. castelnaui* than the control (by 49%; FDR, $p<0.05$; Table 2, Fig 2e–2g). No other fish were significantly affected by the SAFEs, although the numbers of *G. subfasciatus* and *A. australis* followed similar trends as above (LMM, $p>0.05$; Table 2, Fig 2h and 2i).

### Experiment 2: testing a SAFE on an otter trawl

The parsimonious LMM describing drag included SOG and anterior-trawl configuration as main effects, with the latter not significantly different between the control (259.5 ± 5.0 kg) and SAFE (259.7 ± 5.0 kg) trawls ($p>0.05$; Table 2). Irrespective of anterior-trawl configuration, SOG was positively associated with drag (LMM, $p<0.05$).

**Table 1. Scientific and common names and numbers (except blue blubber jellyfish, *Catostylus mosaicus*—weights in kg only) of organisms caught during experiments (Exp.) 1 and 2.**

| *Family* | *Scientific name* | *Common name* | Exp. 1 | Exp. 2 |
|---|---|---|---|---|
| *Cnidarians* | | | | |
| Catostylidae | *Catostylus mosaicus* | Blue blubber jellyfish | 108 | 40 |
| *Crustaceans* | | | | |
| Palaemonidae | *Macrobrachium novaehollandiae* | Freshwater prawn | 2 | – |
| Penaeidae | *Metapenaeus macleayi* | School prawn[1] | 584,044 | 147,116 |
| | *Metapenaeus bennettae* | Green tail prawn[1] | 21 | 49 |
| | *Penaeus monodon* | Tiger prawn[1] | 7 | 3 |
| Portunidae | *Portunus pelagicus* | Blue swimmer crab[1] | 6 | 6 |
| *Elasmobranchs* | | | | |
| Dasyatididae | *Dasyatis* sp | Stingray | – | 1 |
| *Molluscs* | | | | |
| Loliginidae | *Uroteuthis* sp | Squid[1] | 368 | 201 |
| *Teleosts* | | | | |
| Ambassidae | *Ambassis jacksoniensis* | Port Jackson glassfish | 324 | 57 |
| | *Ambassis marianus* | Ramsey's perchlet | 470 | 1,058 |
| Ariidae | *Arius graeffei* | Forktail catfish[1] | 1 | 22 |
| Apogonidae | *Siphamia roseigaster* | Pink-breasted siphonfish | 129 | 65 |
| Carangidae | *Gnathanodon speciosus* | Golden trevally[1] | 1 | – |
| | *Pseudocaranx dentex* | Silver trevally[1] | – | 1 |
| | *Trachurus novaezelandiae* | Yellowtail scad[1] | 1 | 2 |
| Clupeidae | *Herklotsichthys castelnaui* | Southern herring | 400 | 369 |
| | *Hyperlophus vittatus* | Whitebait | – | 5 |
| Engraulidae | *Engraulis australis* | Australian anchovy | 45 | 13 |
| Gerreidae | *Gerres subfasciatus* | Silver biddy | 507 | 447 |
| Hemiramphidae | *Arrhamphus sclerolepis* | Snubnose garfish[1] | 3 | 4 |
| | *Hyporhamphus regularis* | River garfish[1] | 16 | – |
| Monodactylidae | *Monodactylus argenteus* | Diamond fish | 2 | 6 |
| Mugilidae | *Liza argentea* | Flat-tail mullet[1] | 24 | 3 |
| | *Mugil cephalus* | Bully mullet[1] | 1,046 | 64 |
| Muraenesocidae | *Muraenesox bagio* | Common pike eel | 1 | 4 |
| Paralichthyidae | *Pseudorhombus arsius* | Largetooth flounder | 15 | 23 |
| Platycephalidae | *Platycephalus fuscus* | Dusky flathead[1] | 1 | 9 |
| Plotosidae | *Euristhmus lepturus* | Longtail catfish | 61 | 175 |
| Pomatomidae | *Pomatomus saltatrix* | Tailor[1] | 4,087 | 937 |
| Scatophagidae | *Selenotoca multifasciata* | Old maid | – | 1 |
| Sciaenidae | *Argyrosomus japonicus* | Mulloway[1] | 2 | 2 |
| Sillaginidae | *Sillago ciliata* | Sand whiting[1] | – | 2 |
| Soleidae | *Synclidopus macleayanus* | Narrow banded sole | 1 | – |
| Sparidae | *Acanthopagrus australis* | Yellowfin bream[1] | 420 | 328 |
| | *Rhabdosargus sarba* | Tarwhine | 65 | 202 |
| Terapontidae | *Pelates quadrilineatus* | Trumpeter[1] | 13 | 4 |
| Tetraodontidae | *Tetractenos glaber* | Toadfish | 8 | 271 |

–, not present in catches.

[1]economically important

doi:10.1371/journal.pone.0123124.t001

**Table 2. Summaries of Wald *F*-values from linear mixed models assessing the importance of the fixed effect of anterior-trawl configuration (SAFEs vs. controls) in explaining variability among engineering and biological variables.**

| | Experiment 1 Wald *F* | Experiment 2 Wald *F* |
|---|---|---|
| **Engineering variables** | | |
| Wing-end spread | – | 4.19* |
| Drag | 0.62 | 0.004 |
| Hectare trawled | 2.17 | 22.46*** |
| **Biological variables** | | |
| Wt of *Metapenaeus macleayi* 40 $min^{-1}$ | 2.53 | 4.52* |
| Wt of *M. macleayi* $ha^{-1}$ | 2.56 | 0.19 |
| No. of *M. macleayi* 40 $min^{-1}$ | 1.56 | 1.46 |
| No. of *M. macleayi* $ha^{-1}$ | 1.58 | 0.19 |
| Mean CL of *M. macleayi* 40 $min^{-1}$ | 1.55 | 5.41* |
| Wt of fish bycatch 40 $min^{-1}$ | 22.81*** | 12.16** |
| Wt of fish bycatch $ha^{-1}$ | 23.54*** | 7.08* |
| No. of fish bycatch 40 $min^{-1}$ | 19.18** | 9.33** |
| No. of fish bycatch $ha^{-1}$ | 19.75*** | 5.53* |
| No. of *Pomatomus saltatrix* 40 $min^{-1}$ | 15.09*** | 11.93** |
| No. of *P. saltatrix* $ha^{-1}$ | 17.34*** | 10.86** |
| Mean TL of *P. saltatrix* 40 $min^{-1}$ | 1.34 | – |
| No. of *Mugil cephalus* 40 $min^{-1}$ | 5.06** | – |
| No. of *M. cephalus* $ha^{-1}$ | 4.99** | – |
| No. of *Herklotsichthys castelnaui* 40 $min^{-1}$ | 3.94* | 7.00* |
| No. of *H. castelnaui* $ha^{-1}$ | 3.98* | 5.73* |
| No. of *Gerres subfasciatus* 40 $min^{-1}$ | 1.49 | 1.66 |
| No. of *G. subfasciatus* $ha^{-1}$ | 1.24 | 2.39 |
| No. of *Ambassis marianus* 40 $min^{-1}$ | 1.77 | 0.15 |
| No. of *A. marianus* $ha^{-1}$ | 1.45 | 0.01 |
| No. of *Acanthopagrus australis* 40 $min^{-1}$ | 1.00 | 0.11 |
| No. of *A. australis* $ha^{-1}$ | 1.07 | 0.38 |
| No. of *Rhabdosargus sarba* 40 $min^{-1}$ | – | 0.25 |
| No. of *R. sarba* $ha^{-1}$ | – | 0.14 |

Numbers and weights were analysed per 40-min deployment and standardised to per ha trawled calculated using the footrope contact (wing-end spread × distance trawled) and then log-transformed.

–, not relevant.

*$p<0.05$

**$p<0.01$

***$p<0.001$

doi:10.1371/journal.pone.0123124.t002

There was a significant difference in wing-end spreads between configurations, with the control (4.31 ± 0.21 m) spread 0.21 ± 0.05 m wider than the SAFE (LMM, $p<0.05$; Table 2). Both configurations shared a common negative association with STW (LMM, $p<0.01$). The control trawl fished a significantly greater area than the SAFE (1.43 ± 0.10 vs. 1.34 ± 0.10 ha) (LMM, $p<0.001$; Table 2).

The slightly narrower trawl wing-end spread due to the continuous-plastic SAFE was reflected in a significant reduction (~7%) in the weight of *M. macleayi* per 40-min deployment (LMM, $p<0.05$; Table 2, Fig 3a). However, when standardised to per ha, the number and

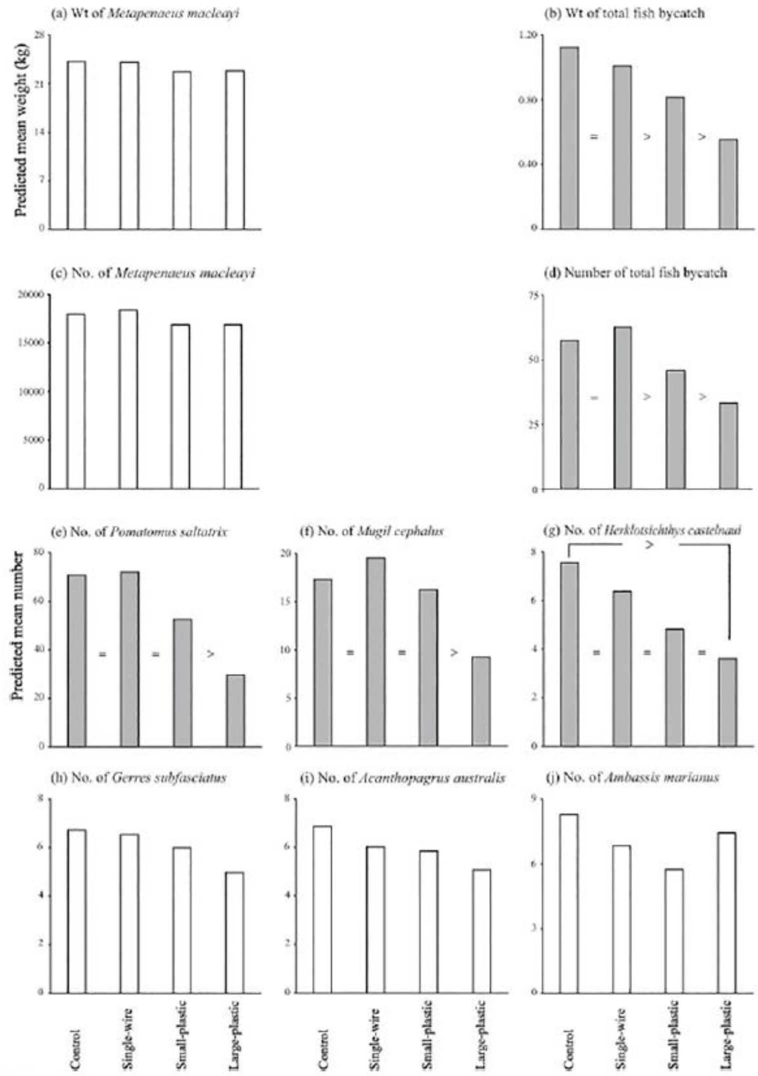


**Fig 2.** Differences in predicted mean weights of (a) school prawns, *Metapenaeus macleayi*, and (b) total fish bycatch, and the predicted mean numbers of (c) school prawns, (d) total fish bycatch, (e) tailor, *Pomatomus saltatrix*, (f) bully mullet, *Mugil cephalus*, (g) southern herring, *Herklotsichthys castelnaui*, (h) silver biddy, *Gerres subfasciatus*, (i) yellowfin bream, *Acanthopagrus australis* and (j) Ramsey's perchlet, *Ambassis marianus* per 40-min deployment between the control and three SAFEs (single-wire, small-plastic and large-plastic) tested in experiment 1. Shaded histograms indicate significant wald *F*-values, while '>' and '=' indicate differences detected in false-discovery-rate pair-wise comparisons ($p<0.05$).

doi:10.1371/journal.pone.0123124.g002

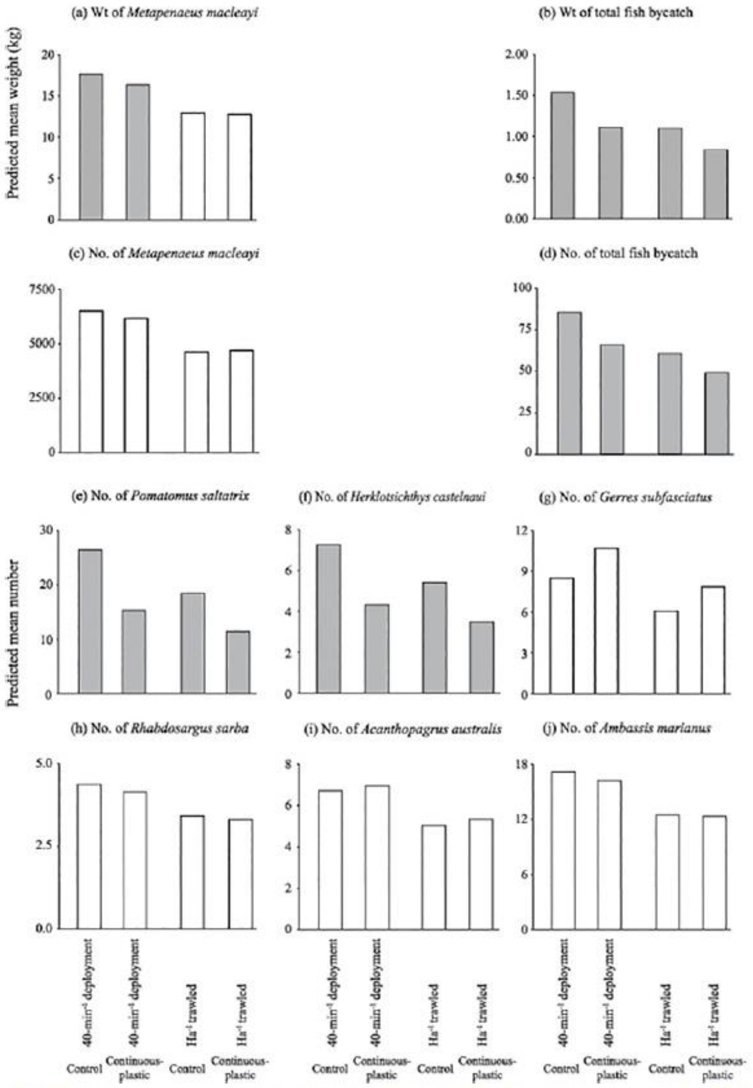


**Fig 3.** Differences in predicted mean weights of (a) school prawns, *Metapenaeus macleayi*, and (b) total fish bycatch, and the predicted mean numbers of (c) school prawns, (d) total fish bycatch, (e) tailor, *Pomatomus saltatrix*, (f) southern herring, *Herklotsichthys castelnaui*, (g) silver biddy, *Gerres subfasciatus*, (h) tarwhine, *Rhabdosargus sarba*, (i) yellowfin bream, *Acanthopagrus australis* and (j) Ramsey's perchlet, *Ambassis marianus* per 40-min deployment and standardised to per ha trawled using the footrope contact (average wing-end spread × distance trawled) between the control otter trawl and that containing the continuous-plastic SAFE tested in experiment 2. Shaded histograms indicate significant differences detected by Wald *F*-values ($p < 0.05$).

doi:10.1371/journal.pone.0123124.g003

weight of *M. macleayi* were not significantly different between trawls (LMM, $p>0.05$; Table 2, Fig 3a and 3c), although the predicted mean CL was significantly smaller in the trawls with the SAFE (14.72 ± 0.20 mm) than the control (14.91 ± 0.20 mm) (LMM, $p<0.05$; Table 2).

Compared to the control, the trawl with the continuous-plastic SAFE caught significantly less total bycatch by weight (by 28%) and number (24%) and fewer *P. saltatrix* and *H. castelnaui* per 40-min deployment and ha trawled (both by up to 42%) (LMM, $p<0.05$; Table 2, Fig 3b and 3d–3f). Catches of the remaining key species were not significantly affected by the continuous-plastic SAFE (LMM, $p>0.05$; Fig 3g–3j).

## Discussion

This study validates the concept of locating simple BRDs anterior to penaeid trawls for improving their species selectivity [13, 14]. Like in our earlier, preliminary study [14], the SAFEs tested here maintained target catches at acceptable limits and, for the otter trawl, the bycatch reductions rivalled those observed for other traditional posteriorly located BRDs [6]. The SAFEs' effectiveness can be discussed firstly according to the utility of the experimental approach, and then the related probable species-specific responses.

The limits/range of the original SAFE concept described by McHugh et al. [14] were somewhat defined in experiment 1 by incrementally testing larger modifications, involving a horizontal wire with and without small and large plastic attachments, across the beam trawl. Specifically, the sizes of the individual plastic strips—~0.23 m long (PP strip and swivel)—were close to what we considered the maximum in terms of not contacting the top of the beam (0.76 m high), each other, nor the substrate during fishing, and potentially impacting on *M. macleayi* catches. However, notwithstanding the considerable bycatch reduction (up to 51%), the maintenance of *M. macleayi* catches at the same levels as the control, suggest that a slightly larger SAFE might have had some utility. Following this logic, we increased the area (from 11 to 23% of the trawl mouth) in the SAFE used on the otter trawl. Further, because the independent plastic strips comprising the SAFEs used on the beam trawl would have been easily entangled among the otter-trawl components (e.g. otter boards and sweep wires as they came together at the surface after each deployment), we chose a continuous-plastic strip.

While the continuous-plastic SAFE did not affect otter-trawl drag, it significantly decreased wing-end spread, the area trawled per deployment, and therefore the catches of *M. macleayi*. The narrower wing-end spread can probably be explained by the drag from the SAFE pulling the otter boards together which would have concomitantly reduced the drag of the trawl and ground-gear [20], providing the observed lack of change in total system resistance. It is also clear that a lower otter-board angle of attack (AOA) would have reduced the effective substrate contact and while speculative, this may have contributed to the negative impacts on *M. macleayi* catches—owing to fewer individuals (potentially those that were larger given the differences in mean size) being disturbed and directed into the path of the trawl [21]. Nevertheless, such catch effects were minimal and could be simply remedied by slightly increasing otter-board surface area.

The differences in wing-end spread due to the continuous-plastic SAFE had no negative effect on fish exclusion, with consistent, significant reductions both per 40 min and ha trawled. The SAFEs also maintained fish reductions between experiments, although the large-plastic SAFE used on the beam was considerably more effective (reducing total bycatch by up to 51% compared to the control) than the continuous-plastic SAFE used on the otter trawl. Although speculative, these results might be explained by the importance of visual cues in affecting fish reactions to towed gears, associated variation in trawl dynamics and potentially other environmental factors [22, 23].

Typically, the trawl capture process depends on fish being herded between the otter boards, sweep wires and trawl wings and then when fatigued, falling back into the codend [24]. This process is strongly affected by the elicited visual cues, whereby as water clarity decreases (e.g. low light or turbid conditions) so too does a fish's ability to detect gear-components and instigate an escape response [9, 15, 22, 23, 25]. Considering the above, in experiment 1 the horizontal wires on the beam remained taut and the plastic strips probably rotated freely and individually, potentially creating a strong visual stimulus for some fish. By comparison, in experiment 2, the continuous-plastic SAFE should have provided less movement and possibly reduced stimulus. Equally important, owing to the shallow concave shape of the SAFE, the angle at the otter boards would have increased, potentially herding some fish in towards the trawl path and negating some of the effectiveness.

Beyond the specific SAFE design, we also suggest that differences in fish density and water clarity may have been important factors contributing towards the observed inter-experimental variation in performances [15, 25]. For example, all three species affected by the SAFEs, but especially *P. saltatrix*, were caught in large numbers (comprising 73 and 32% of the total catches in each experiment). Potentially, intra-specific reactions within schools contributed towards their escape [25]. Future research to refine the SAFE would benefit from assessing the relationship between water clarity and effectiveness. However, because the extremely poor water clarity precludes using cameras, such work will require a manipulative-type experimental approach.

While turbidity was not measured, it was assumed to be comparable between experiments based on the trawling intensity occurring in the area at the time. Available meteorological data (www.bom.gov.au) suggest ambient light may have been lower during experiment 2 with three (of five) days having greater than 50% cloud cover compared to three (of seven) in experiment 1. The selectivity of *H. castelnaui* could have been influenced by the lower ambient light level, which limits the ability of some species to detect trawls [26].

Irrespective of the variability among performances, the observed bycatch reductions, combined with the simplicity and low cost of a SAFE (which should promote adoption as part of a legislated suite of existing, but more complex BRD designs in this fishery) support ongoing testing and refinement. As part of such work, it would be worthwhile to explore ways in which SAFEs could be engineered to concomitantly improve system engineering (and therefore reduce fuel usage). One potential option might be to use the SAFE to more accurately regulate otter-board AOA. It is well established that otter boards represent a large proportion (up to ~30%) of trawl-system drag, which directly correlates to their AOA [27]. Most designs have a high AOA (>30°) to increase stability during deployment, but can have greater operational efficiency at AOAs as low as 20° [27]. Locating an appropriate length of SAFE at the leading edge of otter boards might achieve a lower AOA, and if so reduce some unnecessary system drag. Given the high global price of fuel, even a slight reduction in drag would help to promote industry adoption of the SAFE concept.

Another modification to improve the utility of the SAFE would be to configure a design that maintains a convex shape (away from the trawl mouth); potentially, helping to disperse fish away from the trawl [13]. While this may be difficult to achieve on an otter trawl (due to configuration constraints) such a design might be applicable on a beam trawl, and warrants further testing.

It is clear that trawl gear has evolved to exploit the behavioural and physiological responses of targeted species, but often with concomitant negative impacts on unwanted catches. Retrospectively fitted BRDs have been, and will continue to remain, an important applied strategy for mitigating bycatches, and ideally their associated unaccounted fishing mortality. Based on the results here, the SAFE concept might represent an effective approach for improving the selectivity of penaeid trawls.

## Supporting Information

**S1 Table. Operational data, from sensors (load cells, and GPS), and catch statistics from experiment 1—testing three different SAFEs on a beam trawl.**
(DOCX)

**S2 Table. Operational data, from sensors (load cells, GPS, and NOTUS), and catch statistics from experiment 2—testing a SAFE on an otter trawl.**
(DOCX)

## Acknowledgments

Thanks are extended to Jen Marshall, Chris Barnes, Shiori Naka, and Craig Brand for their technical contributions in the field and laboratory. The authors are grateful for advice provided by the (NSW) Professional Fishermen's Association, Don Johnson, Steve Everson and Greg Skilleter.

## Author Contributions

Conceived and designed the experiments: MJM MKB DJS RBM. Performed the experiments: MJM MKB DJS. Analyzed the data: RBM MKB. Wrote the paper: MJM MKB DJS RBM.

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**Appendix 12.** Broadhurst, M.K., Sterling, D.J. and Millar, R.B. 2014. Traditional vs novel ground gears: Maximising the environmental performance of penaeid trawls. Fish. Res. 167: 199−206.

Fisheries Research 167 (2015) 199–206

Contents lists available at ScienceDirect

Fisheries Research

journal homepage: www.elsevier.com/locate/fishres

# Traditional *vs.* novel ground gears: Maximising the environmental performance of penaeid trawls

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A R T I C L E   I N F O

*Article history:*
Received 30 May 2014
Received in revised form 3 February 2015
Accepted 8 February 2015

*Keywords:*
Drag
Ground gear
Otter trawling
Penaeids
Trawling impacts

A B S T R A C T

The engineering and catching performances of four penaeid-trawl ground gears (all 6.95 m) were compared using a 4.41-m beam-trawl assembly designed to eliminate the confounding effects of other trawl components. Three ground gears comprised either 6- (4.5 and 3.80 kg in air and water), 8- (8.42 and 6.88 kg) or 10-mm (13.07 and 11.20 kg) stainless-steel linked chain, while the fourth was a novel design termed the 'soft-brush' (15.90 and 6.94 kg) and had a buoyed line with vertically suspended 4-mm link chain (giving 63% less bottom contact that the other treatments). The three chain and soft-brush ground gears were used during 24 deployments, producing predicted mean drags (±SE) of 25.49 (1.50), 31.28 (1.50), 39.32 (1.50) and 31.93 (1.50) kgf respectively, or 15, 18, 22 and 18% of the total system. There were no significant differences in numbers or weights of the targeted school prawns, *Metapenaeus macleayi*, but the predicted means were up to 16% lower in the trawls with the 6-mm ground gear. The only species significantly affected by ground gear was small (5.0–8.5 cm total length) forktail catfish, *Arius graeffei*, with the 6-mm catching up to 45% fewer than the 10-mm and soft-brush ground gears; a result attributed to the latter treatments having greater surface areas. The performance of the soft-brush ground gear might be improved by reducing the surface area, while still maintaining target catches and with minimal bottom contact.



## 1. Introduction

More than 100 penaeid species are targeted throughout tropic and temperate regions around the world, supporting numerous and diverse artisanal and industrial fisheries (Vendeville, 1990; Gillett, 2008). A plethora of fishing methods are used, including passive stow and trap nets, but the more common gears are active, encompassing seines (Macbeth et al., 2005), skimmer nets (Hein and Meier, 1995) and especially beam and otter trawls—which typically are fished in multi-trawl configurations (Vendeville, 1990; Gillett, 2008).

Irrespective of the method, owing to the need for bottom contact (to capture the mostly benthic-dwelling penaeids; Coles, 1979) and use in inshore habitats defined by diverse assemblages of species (including juveniles of those that are economically important; Andrew and Pepperell, 1992), there are three broad, historical concerns associated with penaeid fishing: (i) poor selectivity (and subsequent discarding; Andrew and Pepperell, 1992); (ii) high energy usage (Gillett, 2008), and (iii) unwanted benthic impacts (Hutchings, 1990). Wide-scale recognition of these issues, and especially (i) above, has resulted in various technological mitigation strategies; most successful among which are retrospectively fitted devices to the posterior section of the trawl (extension and/or codend) to improve species selection (termed bycatch reduction devices–BRDs; reviewed by Broadhurst (2000)).

Other more ambitious attempts have been made to concomitantly address either (i) and (ii) above or all three concerns via modifications to the anterior sections/components of penaeid trawls. Various modifications, including different mesh materials, twine diameters and sizes (e.g. Sumpton et al., 1989; Broadhurst et al., 2000), spreading mechanisms (Sterling and Eayrs, 2010; Broadhurst et al., 2012a,b, 2013a,b), numbers of trawls (i.e. single- or multi-trawl systems; Andrew et al., 1991; Broadhurst et al., 2013b), and body and frame-line tapers (Broadhurst et al., 2012b) have been shown to affect either the drag, species and size selection and in some cases the total benthic contact.

Despite accounting for >70% of the bottom contact and a considerable proportion of the total weight of trawling systems, one

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http://dx.doi.org/10.1016/j.fishres.2015.02.014

of the least studied anterior components of penaeid trawls is the ground gear. Penaeid-trawl ground gears are diverse, but typically range from simple, relatively light lower frame-lines with clip-on weights (e.g. Silva et al., 2011) to a separate ground line, often comprising heavy chain links, attached to the lower frame-line by so-called chain or rigid metal/plastic 'drops', and with or without a shorter (anterior) 'tickler chain' (FAO, 1972). These configurations are towed between ~0.8 and 2.0 m s$^{-1}$, usually over sand and mud substratum. Similar to nearly all mobile benthic gears (e.g. Watling and Norse, 1998; Thrush and Dayton, 2002), there have been widespread concerns over the physical impacts of penaeid-trawl ground gear (e.g. heavy chains) on habitats, although the real extent of ecosystem consequences are perhaps less clear (Gibbs et al., 1980; Hutchings, 1990; Tanner, 2003; Gillett, 2008; Svane et al., 2009; Prantoni et al., 2013) and likely to vary considerably according to the configurations used. A related issue is the damage done to some organisms that escape under the footrope of the trawl (through/under the ground gear), and the potential for some associated unaccounted fishing mortality (Rose, 1999; Broadhurst et al., 2006).

Irrespective of the severity of benthic impacts, and despite numerous quantitative studies, there have been disproportionally fewer attempts at assessing the utility of alternative technologies to reduce the benthic impacts of penaeid trawls, compared to bycatch reduction—although research has been done with other benthic trawls (reviewed by He and Winger (2010)). It is clear from this latter work that simple variations to conventional ground gears can reduce benthic impacts, and also improve species selectivity (e.g. Brewer et al., 1996; Rose, 1999). Further, although not studied in detail, because such modifications often are inherently lighter and/or have less seabed disturbance, an ancillary effect might include lower drag, and therefore improved fuel efficiency (e.g. Ball et al., 2003).

There are a plethora of potential modifications to ground gears that might address one or more of the above stated historical concerns surrounding penaeid trawling; ranging from simple adjustments within existing configurations (e.g. minimising the size and weight of chains) to completely new rigging arrangements. Among the latter, one novel ground gear that may have application was originally described by Rose (1999) to test the injury rate of red king crab, *Paralithodes camtschaticus* passing under conventional ground gears in Alaskan benthic fish trawls. This configuration comprised a buoyed footrope supporting an array of vertical chains (expired U.S. patent number 5517785), and was subsequent refined and preliminarily tested (termed the 'soft-brush' ground gear) by Sterling and Eayrs (2007). Intuitively, unlike conventional ground gears that are dragged in a concave shape across the bottom, the soft-brush ground gear and derivatives should have considerably fewer habitat impacts because there is no such scraping action. However, a prerequisite to quantifying the extent of any habitat benefits is estimating the engineering and/or catching efficiencies—since any reduction in either or some standardized index of functional performance would preclude industry adoption. We sought to address these latter questions here, by testing the hypothesis of no differences in the catching efficiency and engineering performance of a generic penaeid trawl rigged with three examples of conventional ground gears, and a version of the soft-brush.

Prior to staring the work, one consideration that we recognised with testing different ground gears is that their attachment via drops to the trawl effectively precludes obtaining isolated drag measurements and removes independence, which could confound comparisons. For example, any difference in performance might be due to altered trawl geometry (i.e. different vertical and horizontal openings; Broadhurst et al., 2014), rather than the treatments of interest. A way to avoid such confounding is to ensure the ground gear remains independent of consistent system geometry; achieved here by rigging trawls to a fixed beam and not attaching them to the ground gear. All differences in catches and drag can then be ascribed to just the ground gear.

**Table 1**
Technical specifications of the four ground gears.

| Variable | Ground gear 6-mm | 8-mm | 10-mm | Soft-brush |
|---|---|---|---|---|
| Number of chain links | 270 | 219 | 182 | 150 (drops) |
| Weight in air (g) | 4.55 | 8.42 | 13.07 | 15.90 |
| Weight in water (kg) | 3.80 | 6.88 | 11.20 | 6.94 |
| Linear bottom contact (m) | 6.95 | 6.95 | 6.95 | 2.59 |
| Frontal surface area (m$^2$) | 0.09 | 0.12 | 0.15 | 0.44 |

## 2. Methods

The work was done over eight days during January 2014 in Lake Wooloweyah (sandy and mud substrata in ~1–2 m depth) using a local penaeid trawler (10 m with an 89-kw engine) rigged with two hydraulic winches spooled with 8-mm diameter (ø) stainless warps and 12-m bridles (6-mm Ø stainless wire) (Fig. 1). The trawler was also equipped with a: global positioning system (GPS; Lowrance); two hull-mounted sum logs (EchoPilot, Bronze Log+); and two above-water (Amalgamated Instrument Company–AIC; model no PA6139) and two underwater load cells (Delphi Measurement Pty Ltd) with associated data loggers. The above-water load cells were bolted to each side of the vessel and clamped onto the bridles to measure their tension (kgf). The underwater load cells were configured so that they could be attached to the ground gears of the tested trawls, with 30 m signal-cables extending forward to the vessel (see below).

### 2.1. Fishing-gear configurations

Two beam assemblies (each 108 kg) were used; comprising an aluminium yacht mast (6.00 m long × 0.14 m wide × 0.08 m deep) and galvanized-steel sleds (1.07 m long × 0.76 m high × 0.10 m base plates) fitted at a distance of 4.41 m apart (Fig. 2a). Each beam was assigned to one side of the trawler throughout the experiment. Two identical trawl bodies (each with 7.25-m headlines and foot ropes) were constructed from nominal 35-mm mesh (0.9-mm Ø twisted polyethylene twine) for use with the beams (Fig. 3). Each trawl body was attached to a conventional Nordmøre-grid (28-mm bar spacing) and codend made from nominal 27-mm T45 polyamide mesh (1.25-mm ø braided twine; 120 × 75 B) (Fig. 2a). The footropes of each trawl had twenty-six 6-mm chain drops (135 mm long), and 1.5 kg of 4- and 6-mm chain attached, providing total trawl weights of 15.5 kg (Figs. 2a and 3).

Four ground-gear configurations (all measuring 6.95 m) were constructed for use with the beam trawls (Table 1, Fig. 4a–d). The first three ground gears were links of 6-, 8- and 10-mm stainless-steel chain, respectively and were attached to the bases of the sleds (Table 1, Fig. 4a–c). The fourth treatment was the soft-brush ground gear and comprised 6–mm Ø Dyneema$^{TM}$ braided rope alternately threaded through 74 polyurethane floats (60 × 90 mm) and 74 lengths (260-mm) of 4-mm stainless-steel chain, with another 74 such chains suspended (via two cable ties) singly from each float (Table 1, Figs. 2b and 4d). Four out of every five floats were drilled with four 10-mm diameter holes to achieve neutral buoyancy of the rope during operation. The soft-brush ground gear was attached 100 mm above the base of the sled, so that float line remained suspended above the substrate while ~160 mm of each 4-mm chain made contact (Fig. 2b). Assuming the seabed contact of the soft-brush ground gear was limited to the width of each 4-mm chain (16 mm) and the cable ties (1.3 mm), the total linear contact

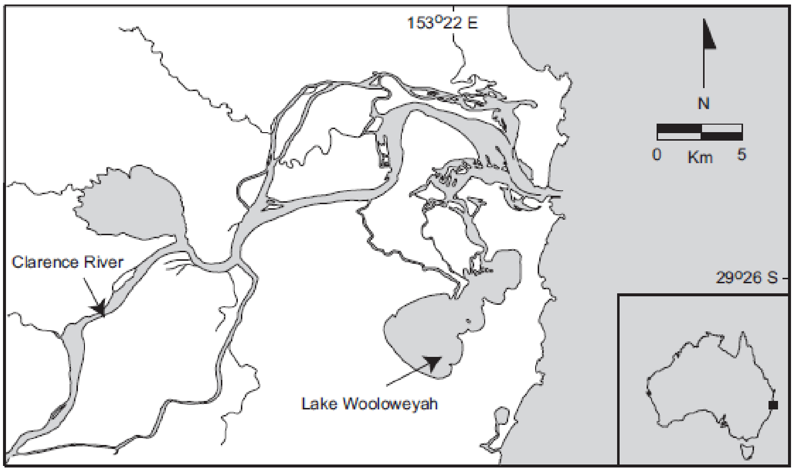


**Fig. 1.** Map of Lake Wooloweyah, NSW, Australia.

was estimated at 2.59 m or 63% less than the chain ground gears (Table 1).

One end of each ground gear was attached to the base of the starboard beam-trawl sled, while the other was secured to the port sled via the underwater load cell (i.e. the end of the ground gear was shackled to the load cell and then to the sled; Fig. 2b). In doing so, the ground gears remained completely independent of the trawls (i.e. they were not attached; apart from a common 1.5 m cord tied at the centre to facilitate retrieval), which ensured the trawl foot ropes and headlines fished at the same vertical height, irrespective of the ground gear (Fig. 2).

### *2.2. Data collected and analyses*

Prior to fishing, the trawl bodies and codends were weighed and 20 randomly selected meshes were measured (SMO). On each fishing day, the trawls were alternately attached to the beam-and-sled assemblies with two of the ground gears and then deployed for

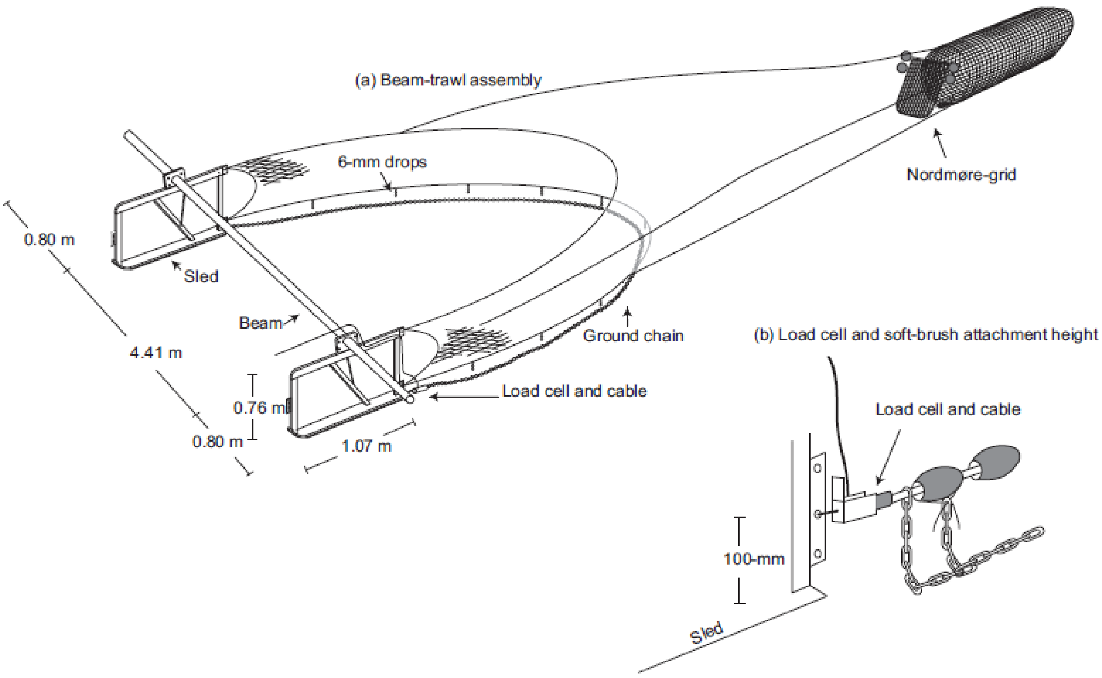


**Fig. 2.** The (a) beam-and-sled assembly and trawl used, with (b) chain ground gear and load cell attached.

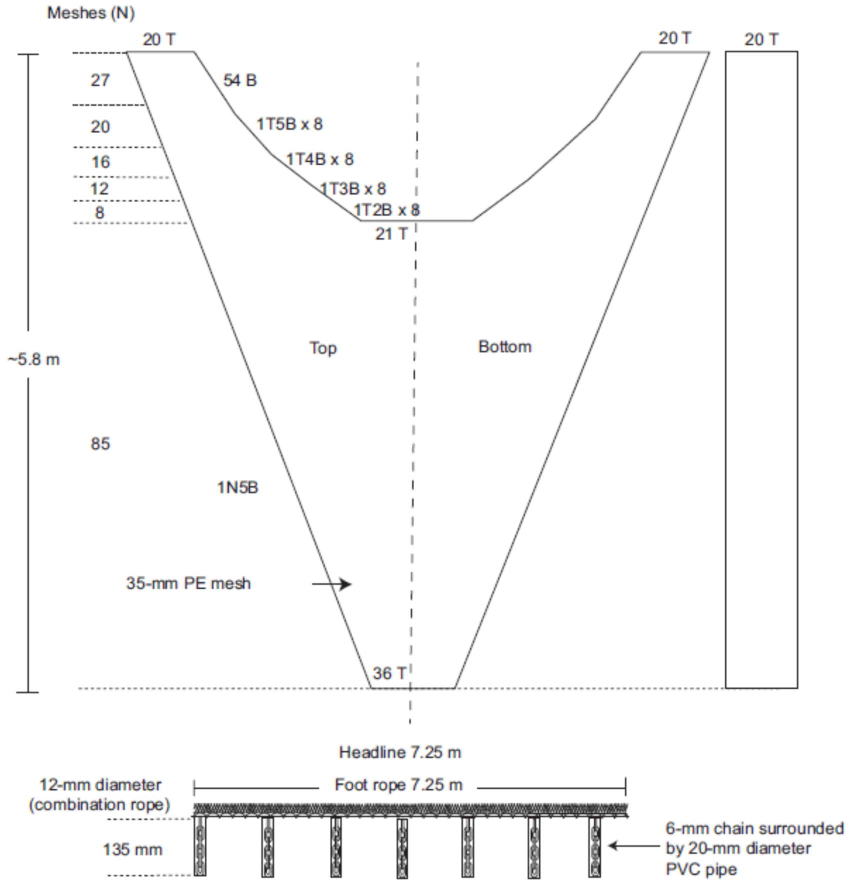


**Fig. 3.** Plan of the penaeid trawl bodies used in the study. N, normals; T, transversals; B, bars; and Ø, diameter.

40 min. The ground gears were then alternated, so that we completed one paired comparison of all four configurations on each day (i.e. six deployments). The trawls were also swapped from side-to-side after the first three deployments, while the pairs of load cells were rotated from side-to-side each day. Over eight days fishing we completed 24 replicate deployments of each ground gear.

The technical data collected during each deployment included the: (i) warp tension (kgf) for each configuration (recorded at 30-second intervals from the above-water load cells—to estimate total system drag); (ii) ground-gear tension (recorded at 30-second intervals from the underwater load cells); (iii) the total distance (m) trawled (sleds on and off the bottom–obtained from the GPS); and (iv) speed over the ground (SOG) and through the water (STW; both in $ms^{-1}$). Biological data collected at the end of each deployment included the: total weights of school prawns, *Metapenaeus macleayi* and bycatch; numbers of each bycatch species; and total lengths (TL in mm) of the most abundant teleosts. Random samples of ~500 g of school prawns were placed into plastic bags and transferred to the laboratory, where they were measured (carapace length–CL in mm), weighed and counted. These latter data were used to estimate the total numbers and the mean CLs caught during each deployment.

The hypothesis of no differences in the mesh sizes within the two trawl bodies or codends was tested in a linear model (LM). Within each experiment, the remaining data were analysed in linear mixed models (LMMs). The numbers and weights of catches were analysed per 40-min deployment and also per hectare trawled (calculated using the known trawl opening and distance traversed) and as log-transformed data so that predicted effects would be multiplicative. All other data, including the mean CL and the number of school prawns per 500 g (a local industry measure; Broadhurst and Millar, 2009) drag and area and distance trawled were analysed in their raw form.

All LMMs included 'ground gear' as a fixed effect, while 'trawls', 'sides' and 'days' and the interactions between 'deployments' and days and between sides and days were included as random terms. For the LMM assessing drags, 'load cells' were included as an additional random term while additional fixed co-variates included 'SOG', 'STW' and 'flow' (calculated as the speed of the current in the direction of travel and defined as SOG–STW). The most parsimonious models were chosen based on the lowest value for a penalised log-likelihood in the form of the Akaike's information criterion. All models were fitted using either the lmer function from the lme4 package or ASReml in the R statistical language, with

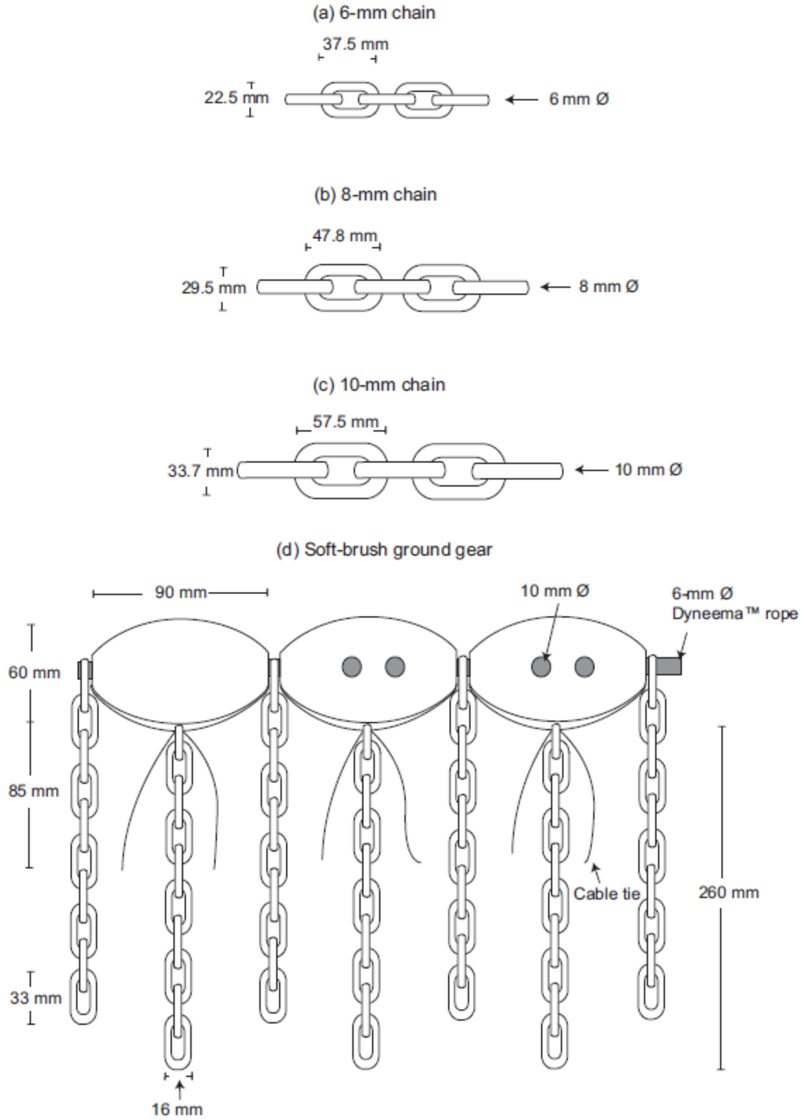


**Fig. 4.** Diagrammatic representation of the (a) 6 mm, (b) 8 mm, (c) 10 mm, and (d) soft-brush ground gears.

the significance of ground gear determined using a Wald *F*. Upon obtaining a significant effect of ground gear, the differences were subsequently explored using the Benjamini-Hochberg-Yekutieli procedure to control the false discovery rate (FDR; Benjamini and Yekutieli, 2001) for multiple pairwise comparisons.

## 3. Results

During 96 replicate deployments of the trawls attached to the four ground gears, 282 and 77 kg of school prawns and bycatch were landed onboard. The bycatch comprised 34 species, although five accounted for >80% of the total, including forktail catfish, *Arius graeffei* (32%; 5.0–8.5 cm TL), southern herring, *Herklotsichthys castelnaui* (30%; 5.0–18.0 cm TL), Ramsey's perchlet, *Ambassis marianus* (8%; 6.0–11.0 cm TL), tarwhine, *Rhabdosargus sarba* (7%; 5.0–14.0 cm TL) and yellowfin bream, *Acanthopagrus australis* (5%; 6.5–22.5 cm TL). These species along with school prawns form the basis of the biological analyses below.

### 3.1. Engineering performances

The SMOs of the tested trawl bodies and codends were not significantly different, with overall means of 34.83 ± 0.05

**Table 2**
Summaries of Wald *F* statistics from linear mixed models assessing the importance of the fixed effect of ground gear (6-m, 8-m and 10-m chain and soft-brush–SB) in explaining variability among technical and biological responses and, where relevant, false-discovery-rate (FDR) adjusted paired comparisons of significant differences among ground gears ($p<0.05$). Excluding the mean CL of school prawns (*Metapenaeus macleayi*), all other numbers and weights log-transformed. – not relevant.

| Technical variables | Wald *F* | FDR |
|---|---|---|
| Hectare trawled | 0.46 | – |
| Speed over the ground | 0.46 | – |
| Total system drag | 20.80*** | 6 < SB = 10; 8 < 10 |
| Ground-gear drag | 436.54*** | 6 < 8 = SB < 10 |
| Biological variables | | |
| Wt of school prawns | 1.30 | – |
| No. of school prawns | 1.43 | – |
| Mean CL of school prawns | 2.75 | – |
| Species number | 1.72 | – |
| Wt of total bycatch | 0.46 | – |
| No. of total bycatch | 4.67** | SB > 6 = 8 |
| No. of forktail catfish | 6.68*** | SB > 6 = 8; 10 > 6 |
| No. of southern herring | 1.53 | – |
| No. of Ramsey's perchlet | 1.24 | – |
| No. of tarwhine | 0.89 | – |
| No. of yellowfin bream | 0.84 | – |

** $p<0.01$.
*** $p<0.001$.

and 27.35 ± 0.10 mm, respectively (LM, $p>0.05$). There were no significant differences in the deployed SOG nor area trawled between the trawls rigged with the 6-mm (1.46 ± 0.01 $ms^{-1}$ and 1.43 ± 0.01 ha), 8-mm (1.45 ± 0.01 $ms^{-1}$ and 1.42 ± 0.01 ha), 10-mm (1.44 ± 0.01 $ms^{-1}$ and 1.42 ± 0.01 ha) nor soft-brush (1.45 ± 0.01 $ms^{-1}$ and 1.43 ± 0.01 ha) ground gears (LMM, $p>0.05$).

The parsimonious LMMs for the total system and partitioned ground-gear drags were both restricted to the main effect of ground gear, which was significant ($p<0.001$; Table 2). Specifically, the beam trawl rigged with the 6-mm ground gear had significantly less drag (163.73 ± 3.54 kgf) than those with both the 10-mm (175.12 ± 3.52 kgf) and soft-brush (170.12 ± 3.53 kgf) ground gears (FDR, $p<0.05$ Table 2). Further, the beam trawl with the 8-mm ground chain (168.09 ± 3.54 kgf) was also significantly easier to tow than that with the 10-mm (FDR, $p<0.05$; Table 2). In terms of actual ground-gear drag, there were significant incremental increases between the 6-mm (25.49 ± 1.50 kgf), 8-mm (31.28 ± 1.50 kgf) and 10-mm (39.32 ± 1.50 kgf), while the soft-brush (31.93 ± 1.50 kgf) had the same drag as the 8-mm (FDR, $p>0.05$), but was significantly different to the rest (FDR, $p<0.05$; Table 2).

### 3.2. Catching performances

Because the areas trawled among treatments were not significantly different, there were no differences in the interpretations of the biological analyses associated with either standardizing catches to per ha or 40-min trawled. The latter therefore are presented for simplicity. Subsequent LMMs detected a significant main effect of ground gear on the numbers of total bycatch and forktail catfish caught; a result mostly explained by the trawls rigged with the soft-brush ground gear catching significantly more than those with the 6-mm (by 1.43 and 3.33 times) and 8-mm (by 1.38 and 2.05 times) (FDR, $p<0.05$; Table 2, Fig. 5d and e). Further, compared to the 6-mm, the trawls with the 10-mm ground gear also caught significantly more forktail catfish (by 1.95 times; FDR, $p<0.05$; Table 2, Fig. 5e). There were no other significant differences detected among catches, including the targeted school prawns, although compared to all other ground gears, the predicted mean weights and numbers were between 12.8 and 15.9% lower in the trawls rigged with the 6-mm ground gear (LMM, $p>0.05$; Table 2, Fig. 5a and b). Similarly, there were no significant differences in the predicted means sizes (SE) of school prawns between the 6-mm (15.00 ± 0.12 mm CL), 8-mm (14.95 ± 0.12 mm CL), 10-mm (15.05 ± 0.12 mm CL) and soft-brush (14.78 ± 0.12 mm CL) ground gears.

## 4. Discussion

This study represents one of the few attempts at assessing the importance of ground gears on the engineering and catching performances of penaeid trawls and, in doing so, contributes towards a growing body of research focusing on minimising the environmental impacts of this important component of mobile gear (Brewer et al., 1996; Rose, 1999; Ball et al., 2003; Shepard et al., 2009). In particular, by eliminating the potential for confounding effects from varying trawl geometries, we have obtained fine-scale estimates of ground-gear contributions towards total system drag and species selectivity; outcomes that can be discussed according to the associated geometric and species-specific responses, and then used to prioritise future research.

In terms of trawling-system drag, the ground gear contribution can be delineated as the sum of components caused through (i) physical benthic contact (i.e. 'scraping') and (ii) hydrodynamic forces (viscous friction and pressure). For the three chain-link ground gears tested here, the above combined to provide a resistance that was some 15–22% of the total system. Given the relatively low profiles of the chain-links, much of their drag can be attributed to (i) above; manifesting as a clear positive relationship with chain-weight, and presumably caused by the heavier chains penetrating more sediment and creating more scraping resistance.

The relationship between the soft-brush ground gear and drag is somewhat more complex. In addition to the longitudinal bottom contact by the 4-mm chains, there were hydrodynamic forces acting on the floats; best illustrated by the large difference in frontal area of this configuration (0.44 $m^2$) compared to the others (0.09–0.15 $m^2$). Specifically, while the bottom contact was some 63% less than all the ground chains, the overall drag was comparable to the 8-mm chain. It might be possible to reduce the drag of the soft-brush to a level approaching the 6-mm or even lower, via different float sizes and/or a more streamlined design. For example, the floats might be turned 90°, or made thinner to present less frontal area.

Any changes to the floats of the soft-brush ground gear would require careful consideration in terms of their species-specific effects on catches. Specifically, the floats would have reduced the escape area below the foot rope, which probably explains the significant increase in catches of forktail catfish by this design; either due to added visual stimulus, or simply tactile responses if collisions occurred. Similar effects might also account for the significantly greater catches of this species in trawls with the 10- rather than the 6-mm ground gears. Given the above, simply minimising float size could reduce the catches of forktail catfish, but could similarly negatively impact on catches of school prawns, although the exact mechanisms probably differ (Watson, 1989).

The behavioural response of school prawns to trawls has not been studied, but work with other penaeids offers insight into their likely responses. For example, it is well established that during the daylight, most penaeids remained burrowed or close to the substratum (Ruello, 1973; Coles, 1979) and so their entry into trawls requires sufficient tactile stimuli to initiate an escape response (involving a contraction of the abdomen). Such stimuli usually is provided by a tickler chain and/or a ground gear with continuous and sufficient bottom contact (Watson, 1989)—a requirement that might explain the slight reduction in catches (although not significant and with no effect on sizes) of school prawns in the trawls with the light 6-mm chain.

The soft-brush had 63% less physical contact with the lake bottom than the chain-link ground gears and so to achieve the same

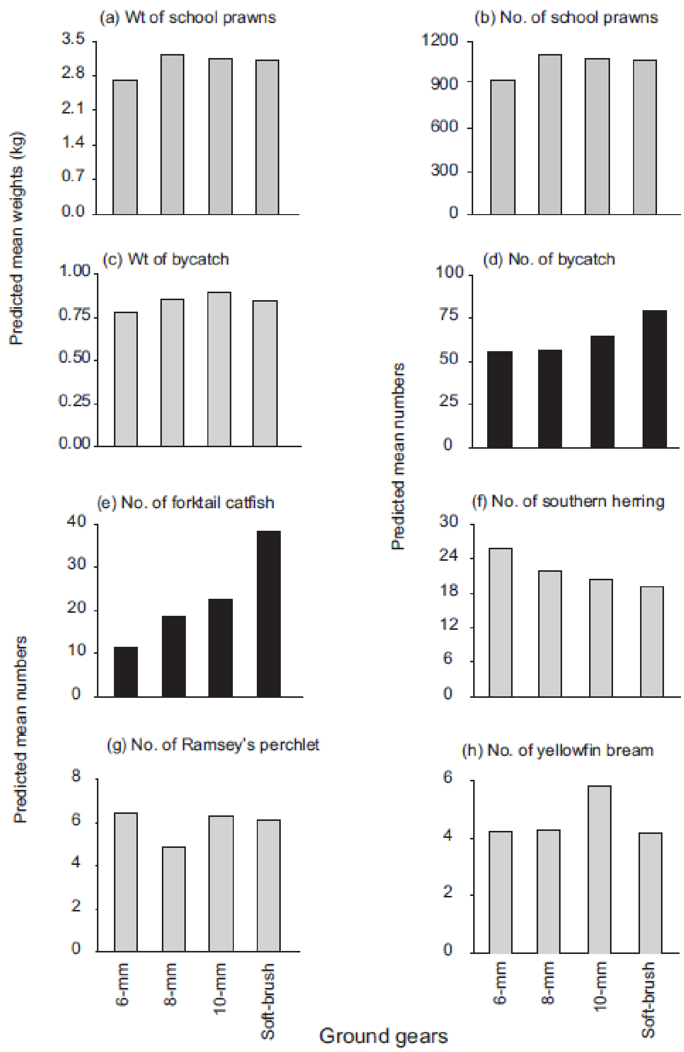


**Fig. 5.** Differences in back-transformed predicted absolute (per 40-min deployment – gray bar plot) and standardized (per ha trawled – white bar plot) mean catches between the 6-mm, 8-mm and soft-brush ground gears and for the (a) weights and (b) numbers of school prawns, *Metapenaeus macleayi*, (c) weights and (d) numbers of total bycatch, and numbers of (e) Port Jackson glassfish, *Ambassis jacksoniensis*, (f) southern herring, *Herklotsichthys castelnaui*, (g) whitebait, *Hyperlophus vittatus*, (h) forktail catfish, *Artus graeffei*, (i) yellowfin bream, *Acanthopagrus australis*, and (j) Ramsey's perchlet, *Ambassis marianus*. Black histograms significant Wald *F*-values detected in linear mixed models ($p < 0.05$).

catches as the 8- and 10-mm treatments may have elicited much of the required tactile stimuli not just from the 4-mm chains, but potentially a hydrodynamic influence of the floats. More specifically, the flow of water around the floats would have meant at least some was displaced downwards which, although speculative, might have stimulated school prawns. The same theory supports using angled cups on the leading edge of dredges to displace water and evoke an escape response among great scallops (*Pecten maximus*) described by Shepard et al. (2009). Assuming comparable effects, any reduction in the size of floats in the soft-brush ground gear might require a concomitant focus of water displacement.

Notwithstanding species-specific differences in catches and their possible mechanisms, both the 6-mm and soft-brush ground gears intuitively would have less benthic impact—especially on infauna and flora. In particular, by being vertically suspended, the chains of the soft-brush would easily slide over sedentary organisms. Such a fishing mechanism was hypothesized to cause the minimal damage to red king crabs observed by Rose (1999).

Within the conventional ground gears, the 8-mm chain appears the best option and indeed is preferred by local fishers, although some use a 10-/8-mm combination. It might be possible to augment capture by rigging a tickler chain (e.g. 2–4 mm chain) and then a light 4–6-mm ground chain. Doing so might still have fewer impacts and less drag than a single 8- or 10-mm chain. The key to such a configuration operating effectively relies on a sufficiently weighted (semi-pelagic) foot rope at an optimal distance off the substratum. Compared to the 10-mm chain, simply choosing 6- or 8-mm would reduce drag by up to 7% for the assessed beam trawl. The differences for an otter trawl would be less noticeable owing to the contribution of drag by the otter boards, but would still represent ~5% drag reduction for the 6-mm ground chain in an otter trawl system that had 20% more drag than the beam-trawl system. Obviously, the ultimate utility of any such configurations would need to be validated using conventional trawls and across the full range of conditions (including different substrate types, depths and weather).

As fuel prices and concerns over habitat damage (and/or escape mortality under foot ropes) increase, it will become more important to assess the impacts and operational characteristics of ground gears used with penaeid trawls. This has previously (largely) been avoided due to the complexity and technical challenges associated with the required experiments. Nevertheless, quantifying the mechanics and importance of ground gears in terms of the engineering and catching efficiencies of penaeid-trawl systems (possibly following similar methodologies as that presented here) will help to progress environmentally sound configurations.

## Acknowledgements

This study was funded by the New South Wales (NSW) Department of Primary Industries and the Australian Fisheries Research and Development Corporation (Grant No. 2011/010). Thanks are extended to the (NSW) Professional Fishermen's Association, Steve Everson, Don Johnson, Jen Marshall, Mitch Burns, Chris Barnes, Nick Sarapuk, and especially Craig Brand.

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**Appendix 13.** Broadhurst, M.K., Sterling, D.J. and Millar, R.B. 2012. Short vs long penaeid trawls: Effects of side taper on engineering and catching performances. Fish. Res. 134–136: 73–81.

Fisheries Research 134–136 (2012) 73–81

Contents lists available at SciVerse ScienceDirect

Fisheries Research

journal homepage: www.elsevier.com/locate/fishres

# Short vs long penaeid trawls: Effects of side taper on engineering and catching performances

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ARTICLE INFO

*Article history:*
Received 11 May 2012
Received in revised form 30 July 2012
Accepted 13 August 2012

*Keywords:*
Bycatch reduction
Drag
Netting taper
Penaeids
Trawl efficiency

ABSTRACT

As part of efforts to minimise unwanted environmental impacts of penaeid trawling, the importance of side taper (and therefore total length) on the (i) engineering performance and (ii) selectivity of a generic trawl was investigated in an Australian fishery. Four designs ('1N2B two-seam', '1N2B four-seam', '1N5B two-seam' and '1N5B four-seam trawls') were tested; all identical (7.35-m headlines and 42-mm mesh) except for their tapers (1N2B—25° to the tow vs 1N5B—35°) and panel number (two vs four). Irrespective of panels, compared to the 1N2B trawls, the shorter 1N5B designs achieved significantly greater predicted mean wing-end spreads (4.7–5.6%), while reducing drag (up to 4.3%) and also the numbers (per ha trawled) of one teleost (southern herring, *Herklotsichthys castelnaui*; by up to 66%). However, catches of the targeted school prawns (*Metapenaeus macleayi*), were also significantly lower in the 1N5B trawls (by up to 50%; and biased towards smaller individuals escaping). The catch reductions were attributed to the shorter 1N5B bodies increasing the probability of mesh encounters (both species) and/or allowing *H. castelnaui* to swim forward and escape.



## 1. Introduction

Penaeids form the basis of important fisheries throughout coastal and estuarine areas of >25 countries in tropical and temperate regions (Gillett, 2008). More than 100 species are targeted, mostly using otter trawls, for an estimated global catch of 1 million mt per annum, or approximately 50% of all wild 'shrimp' (Penaeoidea, Caridea and Sergestoidea) catches (Bailey-Brock and Moss, 1992; Kelleher, 2005; Gillett, 2008).

Owing to their small mesh sizes (usually 30–50 mm; Vendeville, 1990) and use in areas characterised by large assemblages and abundances of small organisms, penaeid trawls typically catch disproportionate quantities of non-target individuals (termed 'bycatch'—including penaeids too small for sale) which are then discarded (Andrew and Pepperell, 1992; Kelleher, 2005). The most recent quantitative estimate (for 1992–2001) of global penaeid-trawl discards was almost 2 million mt per annum, representing >27% of the total from all marine fisheries (Kelleher, 2005).

Concerns over the impacts of large unaccounted discard mortalities on subsequent stocks have resulted in extensive and ongoing efforts at improving penaeid-trawl selectivity (for reviews see Broadhurst, 2000; Broadhurst et al., 2006). Most of this work has involved modifying the posterior section (i.e. the 'codend') to either increase and maintain lateral mesh openings (e.g. square mesh) or, more commonly, install so-called "bycatch reduction devices" (BRDs), which promote the escape of unwanted species via differences in either their behaviour or size (Broadhurst, 2000).

Poor size and species selectivity, and associated unaccounted fishing mortality, are not the only operational challenges facing penaeid-trawl fisheries (Broadhurst et al., 2012). Trawling requires substantial fuel and there is an increasing impetus to improve efficiencies, in terms of reducing both carbon emissions and economic costs (Tyedmers et al., 2005; Priour, 2009). The latter is especially pertinent for developed countries like Australia, where traditionally high labour prices and more recent reductions in catch revenue (due in part to low-priced imported penaeids), and increases in relatively expensive fuel have considerably affected profits (Gillett, 2008). Ultimately, these factors have contributed towards a >40% reduction in the number of Australian penaeid trawlers over the past decade (ABARE, 2001; ABARES, 2011).

At present, the Australian penaeid-trawl industry comprises some 1300 vessels (~8–25 m) towing mostly double-, but also single-, triple- and quad-rigged trawls to target 13 key species in 13 separately managed fisheries, with total annual landings of approximately 20,000 mt valued at A$ 250 million (Gillett, 2008; ABARES, 2011). Like most penaeid-trawl fisheries worldwide, those in Australia have been regulated by various technical input controls (e.g. mesh sizes, headline lengths and numbers of trawls) that more

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0165-7836/$ – see front matter © 2012 Published by Elsevier B.V.
http://dx.doi.org/10.1016/j.fishres.2012.08.009

recently have been updated to include mandatory BRDs and, in some cases, square-mesh codends (Robins et al., 1999; Broadhurst and Millar, 2009).

Such modifications have significantly improved selectivity but none are 100% effective, with most reducing bycatch by 30–70% which, owing to the quantities caught (Andrew and Pepperell, 1992), still potentially represent problematic mortalities (Broadhurst, 2000; Broadhurst et al., 2006). Further, while the adoption and ongoing refinement of BRDs by Australian fishers has partially been promoted via a postulated negative relationship between the amount of bycatch and drag/fuel consumption (e.g. Brewer et al., 1998), the contribution of the codend to total system drag might preclude major effects of BRDs on overall trawl efficiency (Stewart and Ferro, 1987; Priour, 2009). Clearly, to address both the remaining (i) size and species selectivity issues and (ii) inherent poor efficiencies of penaeid trawls, research into ancillary modifications and/or technological developments is required.

A trawl component that could benefit from such research is the anterior section (comprising the 'wings' and 'belly'—collectively termed 'body' here). Although often unregulated, except for mesh size and headline lengths, previous studies have shown that at least some size and species selection occurs throughout penaeid-trawl bodies (Sumpton et al., 1989; Broadhurst et al., 2000). Further, because the body is responsible for 45–80% of the total system drag (Priour, 2009; Sterling and Eayrs, 2010) some modifications should impact efficiency, and especially a reduction in twine area which can be achieved by increasing the angle of the body taper, and shortening the length of the trawl (e.g. Conolly, 1992; Parente et al., 2008).

Australian penaeid-trawl body designs vary considerably, although most have continuous side tapers of between 1N2B (~25° to the towing direction) and 1N5B (~35°), and with either two (top and bottom) or four (top, bottom and two sides) panels (FAO, 1978). Very little work has been done to examine the effects of these design parameters on either the drag or size and/or species selectivity of trawls (but see Conolly, 1992). This study aimed to help address this deficit by assessing the importance of body taper on the catching and engineering efficiencies of a generic Australian penaeid trawl with either two or four panels. The work was done in one inshore fishery in New South Wales (NSW) but, because the chosen trawl design is typical of those used nationally and internationally, the results have broader application across all penaeid-trawl fisheries.

## 2. Materials and methods

### 2.1. Vessel and trawls used

The experiment was done during December 2011 and January 2012 in the Clarence River using a local trawler (10 m and 89 kw) targeting school prawns (*Metapenaeus macleayi*) in ~4–20 m across sandy and mud substratum. The vessel was rigged with two winches; each attached to 8-mm diameter (Ø) stainless-steel wire warps and 40-m bridles (6-mm Ø stainless-steel wire) that were directed laterally and aft through pulleys on two booms (each 6.1 m long from the centre line of the vessel). The bridles were attached to two 1.07-m × 0.76-m rectangular steel otter boards (54 kg each in air) set at 42°, and with 2.89-m sweeps. The trawler was equipped with: a fuel monitor (Floscan series 9000); global positioning system (GPS; Lowrance); attachable load cells and associated data logger (Amalgamated Instrument Company; model nos. PA6139 and TP4); and a portable acoustic, trawl-monitoring system (Notus Trawlmaster System; Model no. TM800ET). The trawl-monitoring system comprised a computer processing unit, hull-mounted omnidirectional hydrophone (located parallel to the vessel winches), and two cylindrical transducers and associated slaves (each 330-mm long × 77-mm Ø; 1.1 kg in water); all designed to be mounted onto the trawl wing-ends.

Four treatment trawls were constructed from nominal 42-mm mesh (inside stretched mesh opening—SMO) twisted polyethylene (PE) twine (1-mm Ø) (Figs. 1 and 2). All trawl designs had identical taper clusters and lengths of headlines (7.35 m) and footropes (8.82 m) and lead-ahead (16.5 meshes), but two different body tapers (1N5B and 1N2B) and numbers of panels (four and two). Based on these differences, the treatments were termed the '1N5B four-panel', '1N5B two-panel', '1N2B four-panel' and '1N2B two-panel' trawls (Figs. 1 and 2). Twine areas were identical in those trawls with the same body tapers (calculated as 3.48 and 5.94 $m^2$ for the 1N5B and 1N2B, designs; Sterling, 2005). All trawls were attached to one of four identical extension sections (100 T × 30 N of nominal 41-mm PE mesh, with 2-mm Ø twine) with Nordmøre-grids installed and codends (120 × 75 B); made from nominal 27-mm polyamide (PA) mesh (1.25-mm Ø twine) hung on the bar (Fig. 2). The trawls had identical stainless-steel ground chains that were slightly heavier than required to ensure bottom contact irrespective of changes in engineering performance.

### 2.2. Trawling, data collected and analyses

Prior to testing, the four trawl designs (and their rigging) were weighed and 15 randomly selected meshes were measured (SMO) in the trawl bodies, extension sections and codends, using a local, purpose-built gauge. On each fishing day, the trawls were alternately attached to the sweeps and otter boards on either side of the vessel, and the net-monitoring transducers and slaves secured at the ends of the inner and outer wings, respectively (Fig. 2). Over six days, at least one 30-min deployment of the six possible pairings of trawls was done daily (i.e. three replicate daily deployments of each treatment), and with an even distribution of treatments between sides of the vessel. On some days, up to two additional replicate paired 30-min deployments were possible.

Various technical and biological data were collected during, and at the end of, each deployment. The technical data included the: (i) drag (kgf) on the bridles attached to each trawl (recorded at 1-min intervals by the load cells); (ii) total fuel (to the nearest 0.1 L) consumed for each paired 30-min deployment (period between otter boards on and off the bottom); (iii) the total distance trawled (*m*—obtained from the GPS); and the (iv) distance of the trawls (from the hydrophone) and (v) wing-end spreads (in m and recorded at 30-s intervals).

At the end of each deployment, catches were separated by codend, and data were collected on the total weights of school prawns and bycatch, the numbers of each bycatch species and total lengths (TL to the nearest 0.5 cm) of the most abundant teleosts. Random samples of ~500 g of penaeids were placed into plastic bags and transferred to the laboratory, where they were measured (carapace length—CL in mm), weighed and counted. The latter data were used to estimate the total number and mean CL caught during each deployment. Random samples of southern herring (*Herklotsichthys castelnaui*; the only teleost affected by trawl design—see Section 3) were also collected and, in addition to TL, measured for their maximum width (MW), height (MH) and girth (MG; all to nearest 0.1 mm). Maximum girth was recorded by placing a 0.5-mm single-strand twine around the fish and then measuring the length with vernier calipers.

The hypothesis of no differences in mesh sizes between the various trawl bodies, extensions and the codends was tested using a linear model (LM). The remaining technical and biological catch data were analysed in linear mixed models (LMMs), with some being standardised prior to analysis. The numbers and weights of catches were standardised to per ha trawled using the swept area of

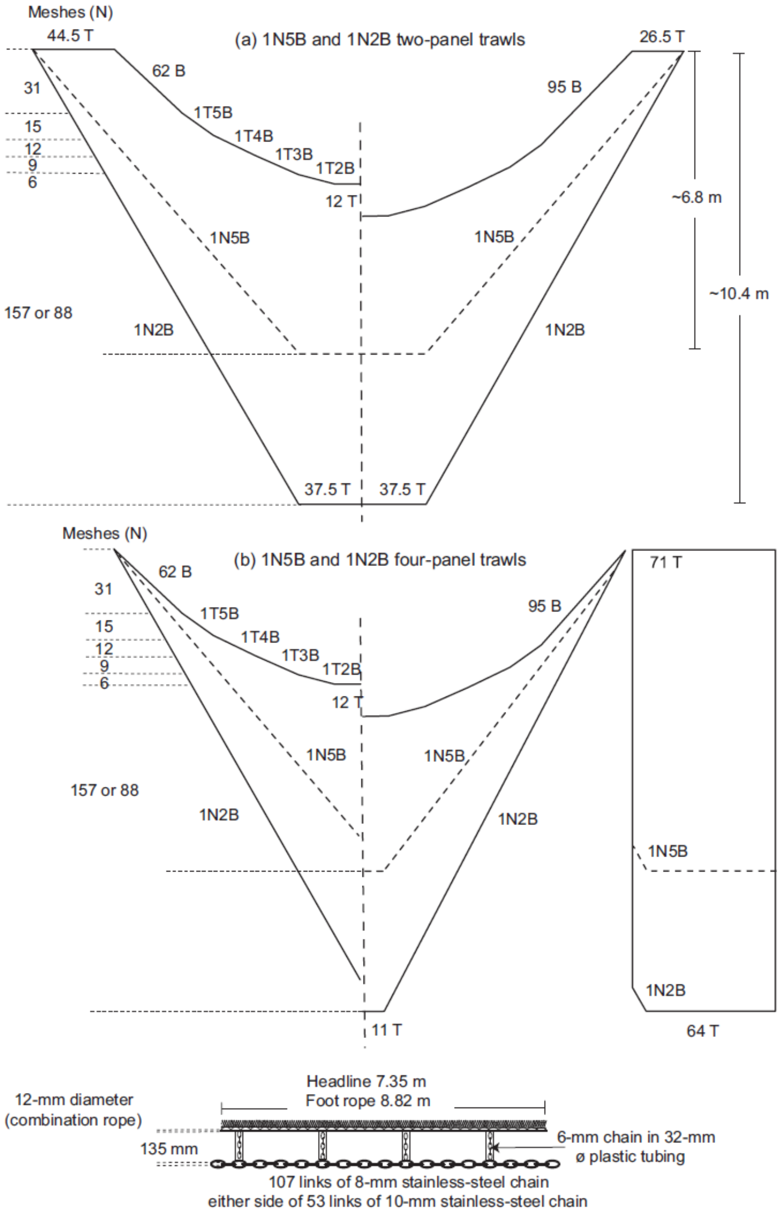


**Fig. 1.** Plans of the (a) 1N5B and 1N2B two-panel and (b) 1N5N and 1N2B four-panel trawls. N, normals; T, transversals; B, bars; and Ø, diameter. Stretched mesh opening was ~42 mm.

the foot rope (i.e. average wing-end spread × the distance trawled) and then log-transformed, so that effects would act multiplicatively. The remaining data, including mean CL and the number of school prawns per 500 g (a local industry measure; Broadhurst and Millar, 2009) drag, wing-end spread, average speed and distance trawled, were analysed in their raw form. All models included 'trawl design' as fixed while 'sides of the vessel', 'days' and the interactions between 'deployments' and days were included as random terms. For the LMM assessing drag, additional random terms involved load cells and their interactions with trawls. All models were fitted

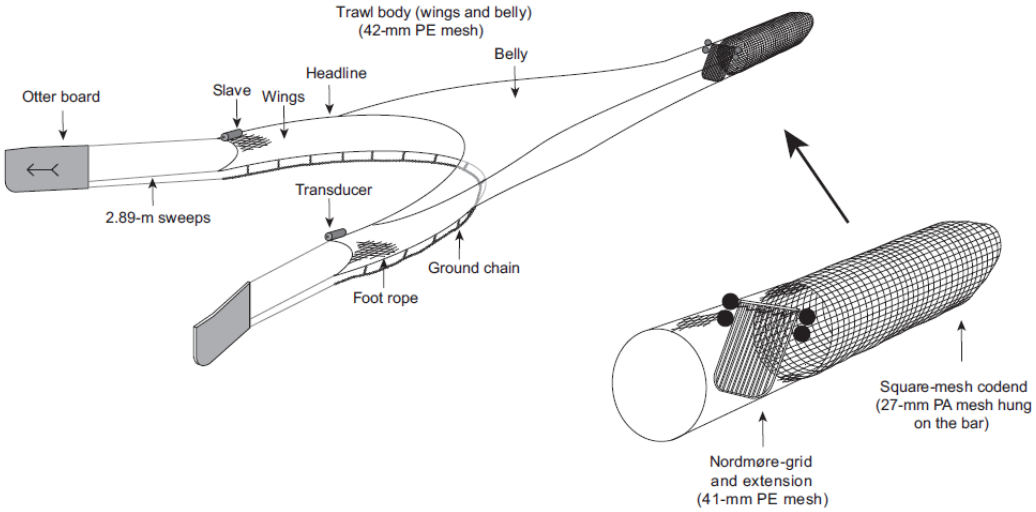


**Fig. 2.** Three-dimensional view of the 1N2B four-panel trawl, and enlarged Nordmøre-grid and square-mesh codend. PA, polyamide; PE, polyethylene.

using the lmer function from the lme4 package of the R statistical language and the significance of trawl design was determined using a likelihood ratio test (LRT). Significant differences were subsequently explored using the Benjamini–Hochberg–Yekutieli procedure to control the false discovery rate (FDR; Benjamini and Yekutieli, 2001), and predicted back-transformed means were graphed. Size–frequency data for key fish were pooled, plotted and graphed, while the morphometric data for southern herring were analysed by linear regression.

Relevant back-transformed predicted means from the LMMs were used to calculate relative fuel consumption associated with towing the four trawl designs. Specifically, assuming that for any given towing speed, the concomitant fuel usage was proportional to the drag, it is possible to determine relative fuel consumption rate using the predicted mean drags. Fuel consumption was standardised to per ha trawled and per kg of school prawns caught for each trawl design by comparing the predicted fuel consumption rate with predicted mean wing-end spread (the rate at which area was being swept for a given trawl speed), and the predicted mean school prawn catches from the respective LMMs. Fuel usage for each deployment was collected to provide the average fuel consumption per trawl per hour of deployment and this was used to scale the effect of trawl design on fuel intensity ($\mathrm{L\,ha^{-1}}$ and $\mathrm{L\,kg^{-1}}$ school prawns).

## 3. Results

During six days of fishing, we completed 20 deployments of each trawl design, although two and one replicates of the 1N5B four- and two-panel trawls, respectively, were excluded owing to fouling (on logs and sticks). The remaining 77 deployments (across all four treatment trawls) had minimal macro debris, although after towing, all trawls had to be shaken free of small particles and sediment that accumulated around some meshes and the ground chains.

The total catches comprised 366 kg of school prawns and 40 kg of bycatch. School prawns were by far the most abundant species by number (98.6%), with the key bycatch comprising freshwater prawns (*Macrobrachium novaehollandiae*), Ramsey's perchlet (*Ambassis marianus*), southern herring, silver biddy (*Gerres subfasciatus*), narrow banded sole (*Synclidopus macleayanus*) and yellowfin bream (*Acanthopagrus australis*) (Table 1). Analyses were restricted to these species, except silver biddy—because most of these (78%) were caught during a single deployment of the 1N2B two-panel trawl.

### 3.1. Technical variables

There were no significant differences in mesh sizes between trawl bodies (overall mean SMO ± SE of 42.08 ± 0.15 mm), extensions (41.40 ± 0.17 mm) or codends (27.35 ± 0.07 mm) (LM, $p > 0.05$). Excluding the otter boards (54.00 kg each) and sweeps

**Table 1**
Scientific and common names and numbers of organisms caught during the experiment.

| Family | Scientific name | Common name | Catch |
|---|---|---|---|
| *Crustaceans* | | | |
| Penaeidae | *Metapenaeus macleayi* | School prawns | 130,671 |
| Palaemonidae | *Macrobrachium novaehollandiae* | Freshwater prawn | 132 |
| Portunidae | *Scylla serrata* | Mud crab | 1 |
| *Teleosts* | | | |
| Ambassidae | *Ambassis jacksoniensis* | Port Jackson glassfish | 59 |
| | *Ambassis marianus* | Ramsey's perchlet | 469 |
| Ariidae | *Arius graeffei* | Forktail catfish | 54 |
| Clupeidae | *Herklotsichthys castelnaui* | Southern herring | 247 |
| Dasyatididae | *Dasyatis* sp. | Stingray | 1 |
| Eleotrinae | *Gobiomorphus australis* | Striped gudgeon | 1 |
| Gerreidae | *Gerres subfasciatus* | Silver biddy | 395 |
| Paralichthyidae | *Pseudorhombus arsius* | Largetooth flounder | 6 |
| Platycephalidae | *Platycephalus fuscus* | Dusky flathead | 4 |
| Plotosidae | *Euristhmus lepturus* | Longtail catfish | 25 |
| Pomatomidae | *Pomatomus saltatrix* | Tailor | 3 |
| Sciaenidae | *Argyrosomus japonicus* | Mulloway | 50 |
| Sillaginidae | *Sillago ciliata* | Sand whiting | 9 |
| Soleidae | *Synclidopus macleayanus* | Narrow banded sole | 168 |
| Sparidae | *Acanthopagrus australis* | Yellowfin bream | 161 |
| | *Rhabdosargus sarba* | Tarwhine | 2 |
| Tetraodontidae | *Tetractenos glaber* | Toadfish | 9 |
| Tetrarogidae | *Notesthes robusta* | Bullrout | 24 |

**Table 2**
Summary of likelihood ratio test (LRT) statistics from linear mixed models assessing the importance of the fixed effect of trawl design (1N2B two-panel – 1N2B2; 1N2B four-panel – 1N2B4; 1N5B two-panel – 1N5B2; and 1N5B four-panel – 1N5B4) in explaining the variability in technical and biological responses and false-discovery-rate (FDR) adjusted paired comparisons of significant differences. The biological variables (excluding the mean carapace length—CL of school prawns and their number per 500 g) were standardized to ha trawled, calculated using the average wing-end spread of the trawls, and then log-transformed.

| | LRT | FDR |
|---|---|---|
| *Technical variables* | | |
| Wing-end spread | 34.67*** | 1N2B2 – 1N2B4 < 1N5B2 – 1N5B4 |
| Trawled area | 30.53*** | 1N2B2 – 1N2B4 < 1N5B2 – 1N5B4 |
| Drag | 10.54** | 1N2B4 > 1N5B2; all others equal |
| *Biological variables* | | |
| Wt of school prawns | 66.91*** | 1N2B2 – 1N2B4 > 1N5B2 – 1N5B4 |
| No. of school prawns | 66.59** | 1N2B2 – 1N2B4 > 1N5B2 – 1N5B4 |
| Mean CL of school prawns | 8.31* | All equal |
| No. of school prawns per 500 g | 8.03* | All equal |
| Wt of total bycatch | 1.85 | |
| No. of total bycatch | 7.39 | |
| No. of Ramsey's perchlet | 5.11 | |
| No. of southern herring | 15.35** | 1N2B2 – 1N2B4 > 1N5B2 – 1N5B4 |
| No. of narrow banded sole | 5.39 | |
| No. of yellowfin bream | 0.62 | |
| No. of freshwater prawn | 5.42 | |

* $p < 0.05$.
** $p < 0.01$.
*** $p < 0.001$.

(2.29 kg in total), the total trawl weights were 29.80 and 31.80 kg for the 1N5B and 1N2B designs, respectively. The four trawl designs were towed at average speeds of between 0.79 and 1.64 m s$^{-1}$ and covered distances of 1.42–2.59 km per 30-min deployment.

The LMMs revealed a significant main effect of trawl design on wing-end spread, trawled area and drag ($p < 0.05$; Tables 2 and 3). False-discovery-rate adjusted paired comparisons for these response variables showed that wing-end spread and trawled area for both the 1N2B two-panel (predicted means ± SE of 4.86 ± 0.04 m and 1.02 ± 0.03 ha) and 1N2B four-panel (4.87 ± 0.04 m and 1.02 ± 0.03 ha) trawls were significantly less than those for 1N5B two-panel (5.15 ± 0.04 m and 1.08 ± 0.03 ha) and 1N5B four-panel (5.11 ± 0.04 m and 1.08 ± 0.03 ha) trawls ($p < 0.001$; Tables 2 and 3). There were no significant differences between trawls with same body tapers for these variables (FDR, $p > 0.05$; Table 2).

Drag was more varied with a significant difference between the 1N2B four-panel (273.32 ± 5.61 kgf) and the 1N5B two-panel trawls (261.54 ± 5.63 kgf; FDR, $p < 0.05$; Tables 2 and 3). However, there were no significant differences for any pair-wise comparisons between the above and the 1N2B two-panel (269.83 ± 5.60 kgf) and 1N5B four-panel (267.67 ± 5.64 kgf) trawls, or within the latter (FDR, $p > 0.05$; Tables 2 and 3). The differences in drag caused similar relative variations in fuel usage (L h$^{-1}$ and L ha$^{-1}$; Table 3).

### 3.2. Biological variables

The significant effects of trawl design on catches were limited to the total number and weight of school prawns per ha trawled, their mean CL and the number per 500 g and the number of southern herring (LMM, $p < 0.01$; Table 2 and Fig. 3a, b and f). Subsequent FDRs revealed no significant differences between trawls with the same body tapers for the total number and weight of school prawns and number of southern herring ($p > 0.05$; Table 2 and Fig. 3a, b and f), but for all three variables, both 1N5B trawls caught significantly less (predicted means reduced by 50–66%) than the 1N2B designs (FDR, $p < 0.01$; Table 2 and Fig. 3a, b and f). For southern herring, these differences appeared to be slightly size dependent, with proportionally fewer small fish in both 1N5B trawls (Fig. 4a). Morphological regressions for this species ($n = 65$) were calculated as MW = 0.13TL − 3.90 ($r^2 = 0.6$), MH = 0.27TL − 2.42 ($r^2 = 0.75$) and MG = 0.63TL + 0.15 ($r^2 = 0.63$), indicating that individuals >13.5 cm TL could not fit through the meshes in the trawl bodies (i.e. perimeter of ~84 mm). The remaining abundant teleost, Ramsey's perchlet, was caught in similar sizes across all four trawl designs (Fig. 4b).

The mean CL and number per 500 g of school prawns could not be separated by FDRs ($p > 0.05$; Table 2). However, similar results were observed as above, with clear inter-taper differences. Specifically, the 1N2B two- and four-panel trawls caught relatively smaller school prawns (predicted mean CLs and number per 500 g of 14.99 ± 0.15 and 14.95 ± 0.15 mm, and 182.44 ± 4.99 and 184.58 ± 4.99, respectively) than the 1N5B two- and four-panel designs (15.17 ± 0.15 and 15.22 ± 0.15 mm CL, and 177.04 ± 5.02 and 175.57 ± 5.05 per 500 g). The smaller sizes of school prawns in the 1N2B trawls were reflected in the size–frequency distributions, with proportionally more individuals between 8 and 11 mm CL retained in these designs, than those with the 1N5B taper (Fig. 5).

## 4. Discussion

This study demonstrated significant effects on the engineering performances and size and species selectivities of penaeid trawls due to the side taper and/or length of the body; all of which remained consistent within either two- or four-panel construction. The magnitudes of the impacts, their associated interpretations and the implications for the ongoing refinement of penaeid-trawl systems need to be discussed with respect to several key study-specific engineering and biological factors.

The consistently greater wing-end spreads (by between 4.7 and 5.6%) achieved by the 1N5B trawls than the shallower-tapered 1N2B designs can be directly attributed to their lower twine area (by ~41% in the body or 2 kg overall), which would have facilitated greater otter board angles of attack. However, while the 1N5B two-panel trawl also had significantly lower drag than the 1N2B four-seam trawl, this difference (4.3%), and the similar (non-significant) trends (including fuel usage) for the other inter-taper comparisons were marginal, and less than what might be expected given the differences in twine area (Sterling, 2005).

The lack of an appreciable drag reduction associated with the 1N5B trawls can be attributed to at least three interrelated factors. First, although substantial, the drag of the netting is only one component of total trawl system drag (Sterling, 2005; Priour, 2009).

**Table 3**
Summary of selected predicted mean performance indicators for the four trawl designs (1N2B two-panel – 1N2B2; 1N2B four-panel – 1N2B4; 1N5B two-panel – 1N5B2; and 1N5B four-panel – 1N5B4). Standard errors are provided in parentheses for data that were analysed in their raw form.

| Trawl design | Wing-end spread (m) | Drag (kgf) | School prawns (kg h$^{-1}$) | Fuel rate (L h$^{-1}$) | Fuel intensity | |
|---|---|---|---|---|---|---|
| | | | | | L ha$^{-1}$ | L kg$^{-1}$ |
| 1N2B2 | 4.86 (0.04) | 269.83 (5.60) | 13.17 | 6.29 | 3.10 | 0.48 |
| 1N2B4 | 4.87 (0.04) | 273.32 (5.61) | 11.95 | 6.37 | 3.13 | 0.53 |
| 1N5B2 | 5.15 (0.04) | 261.54 (5.63) | 6.80 | 6.10 | 2.83 | 0.90 |
| 1N5B4 | 5.11 (0.04) | 267.67 (5.64) | 6.46 | 6.24 | 2.92 | 0.97 |

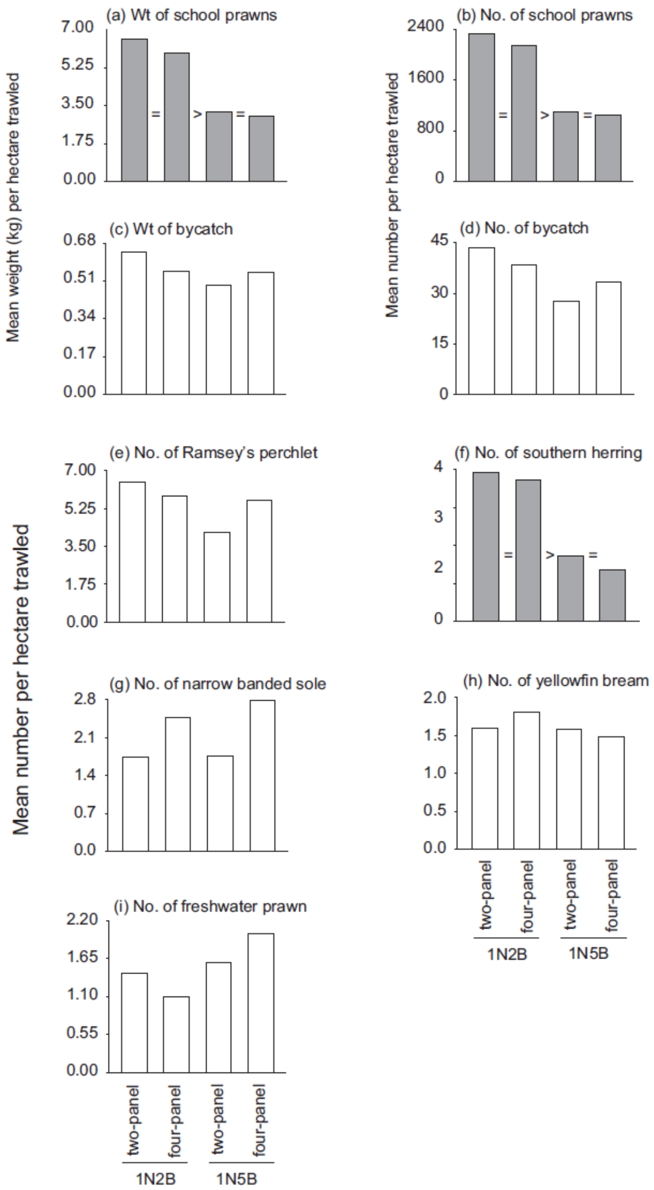


**Fig. 3.** Differences in predicted mean catches per ha trawled between the 1N2B two-panel, 1N2B four-panel, 1N5B two-panel and 1N5B four-panel trawls for (a) weights and (b) numbers of school prawns, *Metapenaeus macleayi*, (c) weights and (d) numbers of bycatch, and numbers of (e) Ramsey's perchlet, *Ambassis marianus*, (f) southern herring, *Herklotsichthys castelnaui*, (g) narrow banded sole, *Synclidopus macleayanus*, (h) yellowfin bream, *Acanthopagrus australis*, and (i) freshwater prawn, *Macrobracium novaehollandiae*. Shaded histograms represent significant likelihood ratio test statistics detected in linear mixed models, while > and = show the direction of differences in false-discovery-rate pairwise comparisons.

Second, because a reduction in netting drag of the 1N5B trawls allowed the otter boards to spread further apart, this increased their angle of attack and concomitantly their drag (Sterling, 2005). Third, the drag of the trawl itself would have increased in response to the greater spread. An additional potential homogenous impact on the drag of all designs may have been the sediment and small particles of weed in the river, which accumulated on knots and had to be shaken free after all deployments.

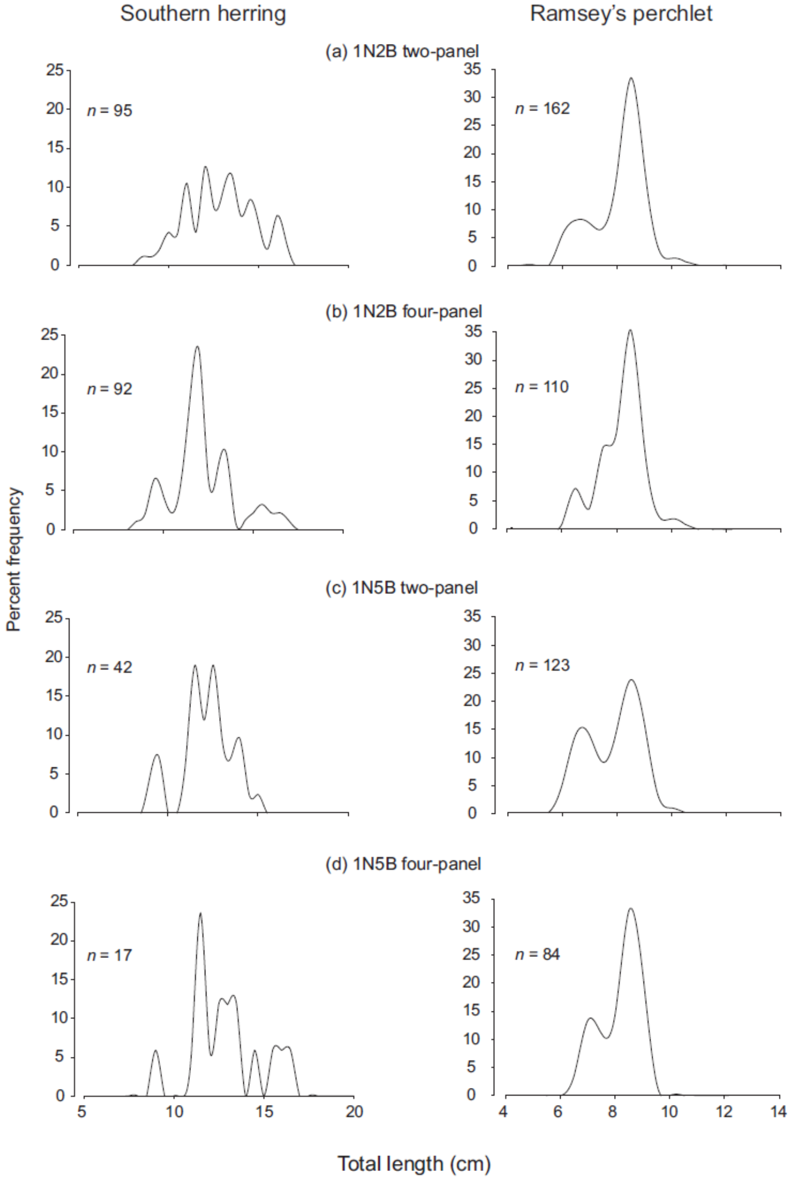


**Fig. 4.** Size–frequency distributions of southern herring, *Herklotsichthys castelnaui*, and Ramsey's perchlet, *Ambassis marianus* from the (a) 1N2B two-panel, (b) 1N2B four-panel, (c) 1N5B two-panel and (d) 1N5B four-panel trawls.

While little can be done to address the fouling of meshes in penaeid trawls, which owing to their use in near shore and estuarine areas is a common problem among many fisheries, the wing-end spread of the 1N5B trawls could be reduced to the same distance as the 1N2B designs, simply by reducing either the size or angle of attack of the otter boards. Doing so would have a cumulative and quite substantial effect on the total system drag because it would directly address two of the interrelated factors discussed above.

The significantly improved spread of the 1N5B trawls was not associated with maintained standardised catches. Rather, the predicted mean catches per ha of school prawns and one species of fish (southern herring), were significantly lower (by up to 65%) than in both 1N2B designs. While the possibility does exist for some

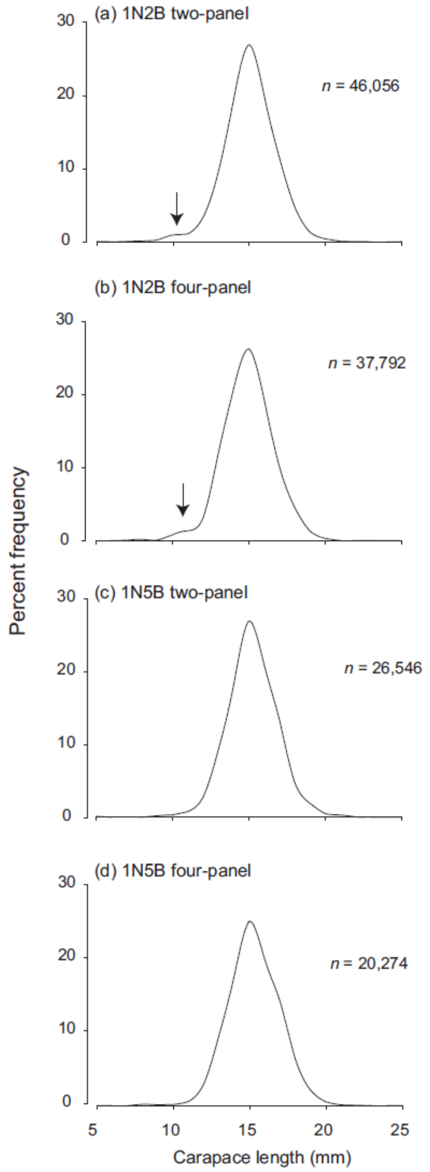


**Fig. 5.** Size–frequency distributions of school prawns, *Metapenaeus macleayi* caught by the (a) 1N2B two-panel, (b) 1N2B four-panel, (c) 1N5B two-panel and (d) 1N5B four-panel trawls. Arrows highlight catches of proportionally more small school prawns by the 1N2B trawls.

variability in inter-taper bottom contact (and therefore catches entering the trawls), the extent of any such differences may have been marginal. Specifically, all trawls were attached to the same heavy otter boards and ground chains, with the latter being heavier than conventional configurations in this fishery. Further, there were no inter-taper differences in the catches of two benthic species (narrow banded sole and freshwater prawn) that were larger than the mesh size, but smaller than the grid spaces (and therefore could not easily escape once in the trawl), which supports comparable benthic contact among configurations. Given the above, perhaps most of the relatively lower catches per ha in the 1N5B trawls can be attributed to the species sizes and specific behavioural responses to the technical characteristics of their steeper tapers.

For example, all of the school prawns (CL mostly <20 mm) could have easily fit through the 42-mm mesh. While any inter-taper differences in fractional mesh opening remain unknown, the greater angle of netting to the direction of towing in the 1N5B trawls (35° vs 25°) would have increased both the probability and normal collision angle of school prawns contacting meshes in the wings and belly as they passed along. In support of this theory, there was clearly a bias towards small prawns escaping (especially 8–11 mm CL), but the substantial reduction in total catches means that this also occurred across all sizes. Given this latter result, the mesh size in this fishery is probably too large and in fact, local trawlers typically configure their anterior trawl sections to minimise lateral openings, with deep wing panels (e.g. up to 75 T) and, in some cases, reverse tapers on the headline and foot ropes to place more meshes into the trawl per unit of wing height (Broadhurst et al., 2012). When combined with side tapers no steeper than 1N3B, such trawl bodies direct quite small school prawns (e.g. down to 5-mm CL) into the codend (e.g. Broadhurst et al., 2004).

Like school prawns, some small southern herring could have escaped through meshes in the wings and bellies of the 1N5B trawls, but this was not evident for other teleosts (e.g. Ramsey's perchlet), most of which were smaller. Also, based on the morphological data, southern herring are quite laterally compressed, and any fish >13.5-cm TL would have a girth exceeding the mesh perimeter (~84 mm) and would not have been able to penetrate the meshes. Southern herring are a schooling species, and at least some may have swum forward and escaped (especially during haul back; Watson, 1989); either from the mouth of the trawl (as proposed for other teleosts by Conolly, 1992), or through the opening at the top of the Nordmøre-grid.

The latter escape mechanism seems likely, since any southern herring that entered the 1N5B trawl would have reached the escape exit of the Nordmøre-grid much faster than those in the 1N2B bodies (which were nearly twice as long in the belly), and they may have had more energy to actively swim through. It also possible that some school prawns passed through the Nordmøre-grids escape exits in the shorter 1N5B trawls, although like most penaeids, they probably remained lower and were directed back into the codend (Watson, 1989). In support of such behaviour, Silva et al. (2011) did not observe significant reductions in penaeid catches (*Xiphopenaeus kroyeri*) from similar-sized Nordmøre-grids in a comparable length (but narrower width) trawl body to the 1N5B designs tested here.

The engineering and biological considerations discussed above have implications for the ongoing refinement of penaeid trawls to address the key environmental concerns of poor efficiencies and species and sizes selectivities. The very low volumes of bycatch (e.g. ~0.5–0.6 kg per 30 min deployment) in this study compared to those prior to the implementation of BRDs (Liggins and Kennelly, 1996) clearly illustrate the effectiveness of the Nordmøre-grid, but it is also clear that refinements to the anterior sections can have cumulative benefits on selectivity (Broadhurst et al., 2000). It would be desirable to identify the main areas where these processes occur (e.g. in the wings or belly for school prawns) and configure lateral mesh openings accordingly. For the Clarence River fishery, a smaller mesh size either throughout or at strategic locations in a 1N5B trawl, might result in more acceptable catches; subsequent use of which should see a greater efficiency in terms of fuel intensity (L $kg^{-1}$ of school prawns).

Irrespective of mesh size, another anterior modification worthy of consideration might include smaller twine diameters. For example, in one of the few studies examining the effects of changing only the type of twine used in the body of penaeid trawls, Sumpton et al. (1989) showed that significantly more smaller-sized prawns (*Penaeus* spp.) and squid (*Loligo* spp.) escaped through the bodies of trawls made from monofilament twine (0.9 mm diameter) than those made from multifilament twine (1.1 mm diameter), and with lower associated drag. Such results further illustrate the potential for addressing two key environmental concerns associated with penaeid trawling through one simple change to an existing configuration.

Research into anterior penaeid-trawl modifications should also focus on otter boards and other spreading mechanisms; not only to reduce total drag, but also to control species selection (e.g. Broadhurst et al., 2012). However, like historical global efforts to develop BRDs for penaeid trawls, it unlikely that a single solution will address all environmental concerns in all fisheries (Brewer et al., 1998; Robins et al., 1999; Broadhurst, 2000; Gillett, 2008). Instead, work should be optimised within a holistic approach that contributes towards a clear framework for broadly prioritising appropriate categories of anterior trawl modifications that can then be applied to address fishery-specific concerns.

## Acknowledgements

This study was funded by the New South Wales (NSW) Department of Primary Industries and the Australian Fisheries Research and Development Corporation (grant no. 2011/010). Thanks are extended to the (NSW) Professional Fishermen's Association, Steve Everson, Don Johnson, Jen Marshall, Mitch Burns, Chris Barnes, Nick Sarapuk, and especially Craig Brand.

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**Appendix 14.** Broadhurst, M.K., Sterling, D.J. and Millar, R.B. 2014. Configuring the mesh size, side taper and wing depth of penaeid trawls to reduce environmental impacts. PLOS One 9(6): e99434. doi:10.1371/journal.pone.0099434.

# Configuring the Mesh Size, Side Taper and Wing Depth of Penaeid Trawls to Reduce Environmental Impacts

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## Abstract

The effects of reducing mesh size while concomitantly varying the side taper and wing depth of a generic penaeid-trawl body were investigated to improve engineering performance and minimize bycatch. Five trawl bodies (with the same codends) were tested across various environmental (e.g. depth and current) and biological (e.g. species and sizes) conditions. The first trawl body comprised 41-mm mesh and represented conventional designs (termed the '41 long deep-wing'), while the remaining trawl bodies were made from 32-mm mesh and differed only in their side tapers, and therefore length (i.e. 1N3B or 'long' and ~28° to the tow direction vs 1N5B or 'short' and ~35°) and wing depths ('deep'–97 T vs 'shallow'–60 T). There were incremental drag reductions (and therefore fuel savings – by up to 18 and 12% per h and ha trawled) associated with reducing twine area via either modification, and subsequently minimizing otter-board area in attempts to standardize spread. Side taper and wing depth had interactive and varied effects on species selectivity, but compared to the conventional 41 long deep-wing trawl, the 32 short shallow-wing trawl (i.e. the least twine area) reduced the total bycatch by 57% (attributed to more fish swimming forward and escaping). In most cases, all small-meshed trawls also caught more smaller school prawns *Metapenaeus macleayi* but to decrease this effect it should be possible to increase mesh size slightly, while still maintaining the above engineering benefits and species selectivity. The results support precisely optimizing mesh size as a precursor to any other anterior penaeid-trawl modifications designed to improve environmental performance.

**Citation:** Broadhurst MK, Sterling DJ, Millar RB (2014) Configuring the Mesh Size, Side Taper and Wing Depth of Penaeid Trawls to Reduce Environmental Impacts. PLoS ONE 9(6): e99434. doi:10.1371/journal.pone.0099434

**Editor:** Athanassios C. Tsikliras, Aristotle University of Thessaloniki, Greece

**Received** March 2, 2014; **Accepted** May 14, 2014; **Published** June 9, 2014



**Funding:** This study was funded by the New South Wales (NSW) Department of Primary Industries and the Australian Fisheries Research and Development Corporation (http://frdc.com.au; Grant no. 2011/010). The funders had no role in study design, data collection and analysis, decision to publish, or preparation of the manuscript.

**Competing Interests:** The employment of David Sterling by the commercial company 'Sterling Trawl Gear Services, 187 Ernest St,10 Manly, Queensland 4179, Australia' does not in any way alter the authors' adherence to PLOS ONE policies on sharing data and materials.

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## Introduction

Benthic otter trawling relies on hydrodynamic forces created by hydrovanes (otter boards) dragged across the seabed to achieve correct net geometry (to capture the targeted animals), and consequently is an energy intensive fishing method [1]. This is especially the case for penaeid trawls which, owing to the small sizes of the targeted species and their distributions (often buried in the soft substratum) [2,3] require small mesh (typically 30–50 mm stretched mesh opening–SMO) and sufficient bottom contact pressure [4]. Such requirements, combined with considerable increases in oil prices over the past decade have resulted in reduced profit margins in many penaeid fisheries [5].

In addition to creating considerable drag, the spatial use (i.e. typically inshore tropical and temperate regions) of small-meshed penaeid trawls means that they generally retain disproportionate quantities of bycatch, including juveniles of commercially and recreationally important species [6]. More specifically, despite contributing towards <1.5% of the total harvest from marine capture fisheries, penaeid trawling is responsible for approximately one quarter of global discards [5,7]; much of which is associated with considerable mortality and the implicit assumption of negative impacts on some stocks [8].

The above concerns over high energy intensities and poor size and species selectivities of penaeid trawls have mostly been separately assessed; typically through on-going industry-based efforts at improving operational efficiencies [9], and more collaborative work with scientists to develop physical modifications to codends (posterior sections of trawls) that improve selectivity (i.e. bycatch reduction devices –BRDs) [10]. However, both of these issues might be concomitantly addressed by modifying the anterior trawl section (or rigging), including the: number of trawls (i.e. single- or multi-trawl systems) [6,11]; spreading mechanisms [9–13]; body and frame-line tapers [14,15]; and especially the material, twine diameter and size of mesh [16–18]. The mesh characteristics are particularly important, since not only do the lateral openings ultimately influence what escapes or is retained (for small animals), the twine typically comprises >70% of the total system area for most penaeid trawling systems, and therefore strongly affects drag.

In many cases, changing any of the above parameters within the anterior trawl section will influence catching and engineering performances, although there are clearly dominant factors and often complex and interactive relationships [11–13,15,17]. For example, in a recent study in an Australian penaeid-trawl fishery, we demonstrated the utility of shorter trawls (via increasing body taper from 1N2B to 1N5B, or the netting angle to the direction of towing from ~25 to 35°) for significantly reducing the bycatch of one teleost (southern herring *Herklotsichthys castelnaui*) by up to 66% and also drag [15], although there was also some loss of penaeids (school prawns *Metapenaeus macleayi*). The lower school prawn catches were hypothesized to be caused by an increase in their collision probability (i.e. more acute angles of netting) against too large a mesh (legal mesh size is ≥40 mm SMO in this fishery) for the targeted sizes (mean carapace lengths–CL of >~15 mm) [19]. By comparison, most southern herring were larger than the mesh and probably escaped more easily either through the posteriorly located BRD, or from the mouths of the shorter trawls [15].

These results highlight the need to ensure the most appropriate mesh size and/or rigging arrangements to maintain consistent lateral openings in trawl bodies as a precursor to examining other changes designed to improve selectivity and reduce drag. However, it is also important to consider that irrespective of the mesh size, various design factors also affect lateral openings [16]. One potentially important variable is the area of netting in the trawl wings (typically controlled by depth or the number of meshes in the transverse direction), which varies considerably among designs. Because the headline height of many penaeid trawls is largely determined by the height of the otter boards, unlike fish trawls, varying wing depth will not necessarily affect the vertical trawl opening, but concomitant differences in associated twine area should impact on drag and potentially selectivity [16].

Given the above, this study sought to contribute to recent efforts aimed at holistically reducing the environmental impacts of penaeid trawling through modifications to the anterior section, by assessing the utility of more closely matching mesh size to the targeted species while concomitantly examining the importance of body taper and twine area in the wings as means for reducing drag and improving species and size selectivity. The work was done within one Australian penaeid-trawl fishery, but the results are applicable to international fisheries.

## Materials and Methods

### Ethics statement

The research was done in Lake Wooloweyah (29°26′ S 153°22′ E) and the Clarence River (29°27′ S 153°12′ E) New South Wales (NSW) Australia and in accord with the Department of Primaries Industries scientific collection permit (No. P01/0059(A)-2.0). No specific permissions were required for the locations. The field studies did not involve endangered or protected species. Animal ethics approval for the research was granted by the NSW DPI Animal Care and Ethics Committee (Ref. 08/06).

### Location and vessel

The work involved two experiments completed between October 2012 and April 2013 in Lake Wooloweyah (experiment 1) and the Clarence River (experiment 2), using a double-rigged trawler (10 m and 89 kw) fishing in ~1–18 m across sandy and mud substrata (Figure 1a). The vessel had two winch drums; each holding 8-mm diameter–Ø stainless warps and 40-m bridles (6-mm Ø stainless wire) (Figure 1a). The trawler was also equipped with: a fuel monitor (Floscan series 9000); global positioning system (GPS; Lowrance); hull-mounted sum log (EchoPilot, Bronze Log+), warp-attachable load cells and associated data logger (Amalgamated Instrument Company; model nos PA6139 and TP4); and a portable acoustic, trawl-monitoring system with wing-end distance sensors (Notus Trawlmaster System; Model no. TM800ET) [13].

### Trawl configurations and otter boards

Five trawl bodies (encompassing wings and belly) were assessed; all with the same headline and footrope lengths (7.35 m), ground gear configurations, sweeps (2.89 m) and identical color and twine material, and length-for-length clusters of headline and foot-rope tapers (Figures 1 and 2, Table 1). One of the trawl bodies was a conventional design used in the Clarence River and made from nominal 41-mm (stretched mesh opening–SMO) mesh (1.20-mm Ø twine) with a side taper of 1N3B and termed the '41 long deep-wing' (Figures 1 and 2, Table 1). The remaining four trawl bodies were constructed from nominal 32-mm (SMO) mesh and narrower 0.88-mm Ø twine (to maintain a constant twine-Ø-mesh-size ratio among designs) and differed only in their wing depths (deep−97 vs shallow−60 T) and side tapers (long−1N3B vs short−1N5B) (Figure 2, Table 1). The four smaller-mesh trawls were termed the (1) '32 long deep-wing' (same dimensions as the 41-long deep-wing trawl including twine area, but smaller mesh); (2) '32 long shallow-wing'; (3) '32 short deep-wing'; and (4) '32 short shallow-wing' (Figures 1 and 2, Table 1). All trawl bodies had the same knot directions providing up force on the top and bottom panels and out force on the side panels and were rigged with Nordmøre-grid BRDs in nominal 41-mm extension sections and square-mesh codends made from nominal 27-mm polyamide mesh hung on the bar (Figure 1b).

The four otter boards were flat rectangular (1.39×0.61 m) and, via two removable slotted timber planks, adjustable to three surface areas (0.85, 0.73 and 0.61 $m^2$; Figure 1c, Table 1). During experiment 1, the water was shallow (<2 m) and the trawls were deployed with only ~10-m of bridle (Figure 1a). Therefore to achieve sufficient spread at the high bridle angle, the largest area (0.85 $m^2$) otter boards were used with all trawls (Figure 1c, Table 1). In contrast, during experiment 2 in the deeper (mostly 10–18 m) Clarence River, 40-m bridles were deployed for all hauls and otter-board areas were configured in an attempt to achieve similar (and optimal) wing-end spreads among the different trawls (Figure 1a and c, Table 1).

### Experimental design and data collected

Prior to testing, the five trawls were weighed and 15 randomly-selected meshes were measured using a local, purpose-built mesh gauge in the bodies, extensions and codends for SMO (Table 1). On each fishing day, the trawls being tested were alternately attached to the sweeps and relevant otter boards on each side of the vessel, and the Notus distance sensors and slaves secured at the ends of the inner and outer wings (Figure 1b). After each trawl was deployed, the load cells were attached to the towing wires.

There were 10 possible paired combinations of the five trawls, but it was only practical to complete five deployments (40-min) on each day. Therefore, in each experiment, we assessed all combinations over two-day blocks, providing two daily replicates of each trawl on each day. Over seven and twelve days of fishing in Lake Wooloweyah and the Clarence River, this provided 14 and 24 replicate deployments (attempting conventional target SOGs of ~1.20 $ms^{-1}$) of each trawl, with an even distribution of treatments between sides of the vessel.

The technical data collected during each deployment included the: (1) drag (kgf) of each configuration; (2) the total distance trawled (otter boards on and off the bottom – obtained from the plotter and trawl-monitoring system); (3) speed the ground (SOG) and through the water (STW; both in $ms^{-1}$), (4) depth of fishing, (5) distance of the trawls behind the vessel, and (6) the wing-end spreads (all in m). All data were recorded at 60-s intervals. During experiment 1, the shallow water and interference from the propeller wash precluded simultaneous data acquisition from the

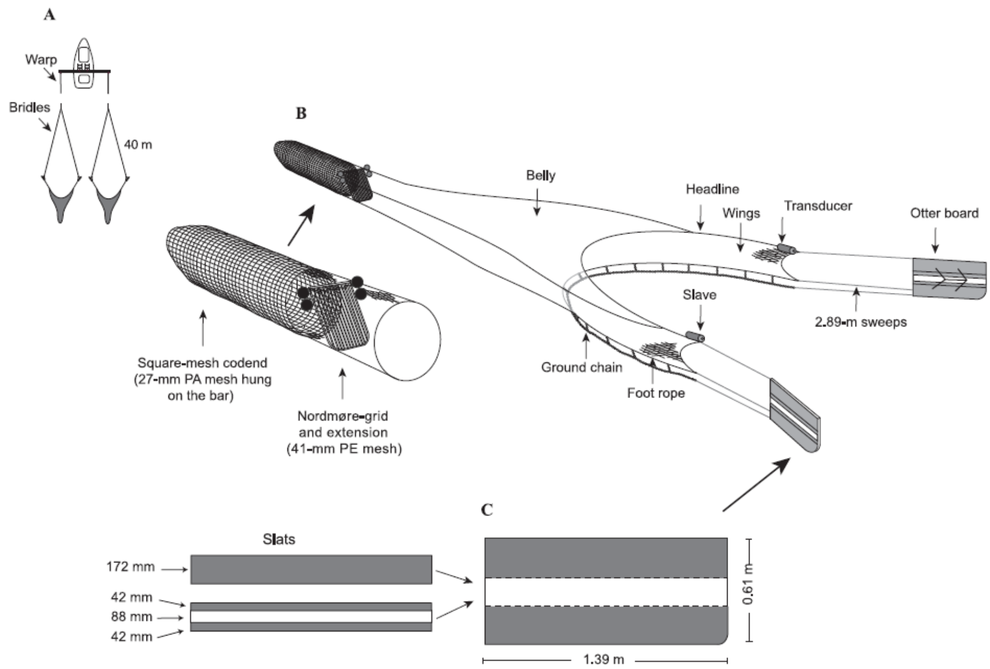


**Figure 1. Diagrammatic representation of the (A) double-rig configuration, (B) 32 long shallow-wing trawl, and enlarged Nordmøre-grid and square-mesh codend and (C) otter boards with two removable slots.** PA, polyamide; and PE, polyethylene.
doi:10.1371/journal.pone.0099434.g001

paired trawls by the hydrophone, and so it was positioned in front of each trawl for half the deployment (i.e., ~20-min of wing-end spread data for each trawl). Both trawls were simultaneously monitored throughout the deployments in experiment 2.

Biological data were also collected at the end of each deployment and included the: total weights of school prawns and bycatch; numbers of each bycatch species; and total lengths (TL to the nearest 05 cm) of the most abundant teleosts. Random samples of ~500 g of school prawns were placed into plastic bags and transferred to the laboratory, where they were measured (CL in mm), weighed and counted. The latter data were used to estimate the numbers and weights of 'optimal' commercial ($\geq$ 15 mm CL) and sub-commercial (<15 mm CL) school prawns during each deployment.

## Statistical analyses

The hypothesis of no differences in the mesh sizes of the various trawls, extensions and codends was tested in separate linear models (LM), and any significant differences subsequently explored using the Benjamini-Hochberg-Yekutieli procedure to control the false discovery rate (FDR) [20]. Within each experiment, the remaining technical and biological data were analyzed in linear mixed models (LMMs), with some standardized prior to analyses. To remove any confounding effects of slightly different wing-end spreads (see Results), the numbers and weights of catches were standardized to per ha trawled using the swept area of the foot rope (calculated by average wing-end spread × the distance trawled) and then log-transformed so that differences between gears would act multiplicatively rather than additively. Predicted mean numbers and weights (per ha) were obtained by back-transforming. All other data, including the mean CL per deployment, drag, wing-end spread, SOG, STW and distance trawled were analyzed in their raw form.

All models included 'trawl' as fixed, while 'trawl sides' and 'days' and the interaction between 'deployments' and days were included as random terms. For the LMM assessing drag and spread, additional random terms involved load cells and the paired Notus sensors, respectively while additional covariates included SOG, 'current' (calculated as the speed of the water in the direction of travel and defined as SOG–STW), distance aft of the trawl configuration from the vessel and fishing depth. All models were fitted using the lmer function from the lme4 package of the R statistical language and the significance of trawl design was determined using a likelihood ratio test (LRT). Significant differences were investigated using FDR pair-wise tests.

Predicted means from the LMMs for drag were used to calculate relative fuel consumption associated with towing the five trawls. Specifically, assuming that for any given towing speed, the concomitant fuel usage was proportional to the drag, it is possible to determine relative fuel consumption rate using the predicted mean drags. Fuel consumption was standardized to per ha trawled for each trawl design by comparing the fuel consumption rate with predicted mean wing-end spread (the rate at which area was being swept for a given trawl speed) from the relevant LMMs.

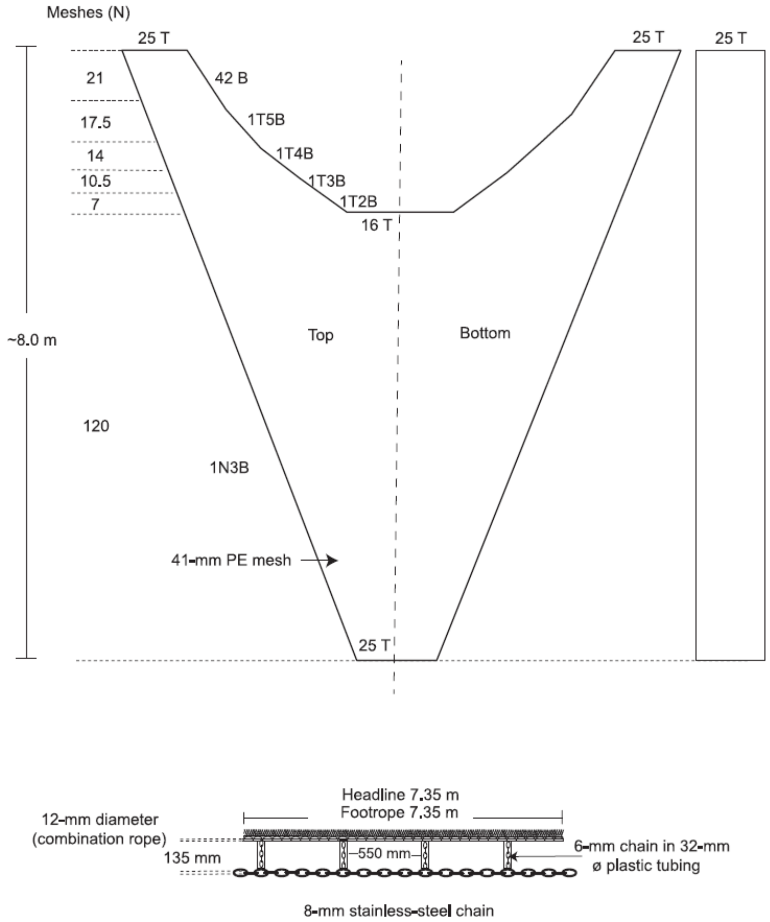


**Figure 2. Plan of the conventional 41 long deep-wing trawl. N, normal; T, transversals; B, Bars; and Ø, diameter.**
doi:10.1371/journal.pone.0099434.g002

## Results

There was a significant difference in SMO between the 41-conventional trawl (mean ±SE of 41.43±0.11 mm) and the four smaller-meshed designs (LM, $p<0.001$), but no significant differences among the latter (FDR, $p>0.05$; overall mean ±SE of 31.61±0.08 mm). There were no significant differences in SMO among the extensions (41.50±0.24 mm) and codends (27.37±0.10 mm) (LM, $p>0.05$).

Pooled across experiments, the five trawls caught 1511 and 119 kg of school prawns and bycatch (Table 2). The total bycatch included 31 species but in experiment 1, tailor *Pomatomus saltatrix* (ranging in size from 4.0–20.0 cm TL), Ramsey's perchlet *Ambassis marianus* (5.0–11.0 cm TL), and southern herring *Herklotsichthys castelnaui* (6.0–17.0 cm TL) comprised 85% of catches, while in experiment 2, forktail catfish *Arius graeffei* (7.0–19.0 cm TL) represented 83% of catches. These three species, along with school prawns, form the basis of the biological analyses (Table 2).

### Experiment 1: Lake Wooloweyah

The five trawl designs were towed at SOGs of between 1.17 and 1.43 $ms^{-1}$, covering distances of between 3.12 and 3.87 km. There were significant differences in wing-end spread and drag among trawls (LMMs, $p<0.001$; Tables 3 and 4). The only appropriate fixed effect in the LMM for wing-end spread was trawl, with the predicted mean (±SE) wing-end spread of the 32 short shallow-wing trawl (4.47±0.05 m) significantly greater than both the 41 (4.29±0.05 m) and 32 long deep-wing trawls (4.27±0.06 m) (FDR, $p<0.05$; Table 4). No significant differences were detected among the wing-end spreads of the above trawls and either the 32 long shallow-wing (4.40±0.05 m) or short deep-wing trawls (4.31±0.05 m) (FDR, $p>0.05$; Table 4).

**Table 1.** Technical specifications of the trawls and rigging.

| | | 41 long deep-wing | 32 long deep-wing | 32 long shallow-wing | 32 short deep-wing | 32 short shallow-wing |
|---|---|---|---|---|---|---|
| Trawl body | Stretched mesh opening (mm) | 41.33 | 31.60 | 31.60 | 31.60 | 31.60 |
| | Twine diameter (mm) | 1.10 | 0.88 | 0.88 | 0.88 | 0.88 |
| | Wing end (T) | 75 | 97 | 60 | 97 | 60 |
| | Wing end (stretched m) | ~3.20 | ~3.20 | ~1.92 | ~3.20 | ~1.92 |
| | Headline and footrope tapers (half trawl) | 42 AB; 7 × (1T5B; 1T4B; 1T3B and 1T2B); and 16 T | 54 AB; 9 × (1T5B; 1T4B; 1T3B; and 1T2B); and 21 T | 54 AB; 9 × (1T5B; 1T4B; 1T3B; and 1T2B); and 21 T | 54 AB; 9 × (1T5B; 1T4B; 1T3B and 1T2B); and 21 T | 54 AB; 9 × (1T5B; 1T4B; 1T3B; and 1T2B); and 21 T |
| | Body/wing side tapers | 1N3B | 1N3B | 1N3B | 1N5B | 1N5B |
| | Wing length (N) | 70 | 90 | 90 | 90 | 90 |
| | Belly length (N) | 120 | 155 | 124 | 116 | 90 |
| | Belly length (m) | ~5.1 | ~5.1 | ~4.1 | ~3.8 | ~2.9 |
| | Posterior body circumference (T) | 150 | 194 | 194 | 194 | 194 |
| | Weight (kg) | 27.60 | 29.32 | 28.23 | 28.41 | 27.50 |
| | Total twine area ($m^2$) | 4.80 | 4.95 | 3.64 | 3.86 | 2.75 |
| Otter boards | Individual area ($m^2$) used in the lake | 0.85 | 0.85 | 0.85 | 0.85 | 0.85 |
| | Individual weight (kg) used in the lake | 51.90 | 51.90 | 51.90 | 51.90 | 51.90 |
| | Individual area ($m^2$) used in the river | 0.85 | 0.85 | 0.73 | 0.73 | 0.61 |
| | Individual weight (kg) used in the river | 51.90 | 51.90 | 50.60 | 50.60 | 49.30 |
| Total system | Area ($m^2$) used in the lake | 7.07 | 7.22 | 5.91 | 6.12 | 5.02 |
| | Weight (kg) used in the lake | 133.68 | 135.40 | 134.31 | 134.49 | 133.58 |
| | Area ($m^2$) used in the river | 7.07 | 7.22 | 5.67 | 5.88 | 4.54 |
| | Weight (kg) used in the river | 133.68 | 135.40 | 131.71 | 131.89 | 128.38 |

Each trawl body was attached to an extension section with a Nordmøre-grid installed and codend (total weight of 5.80 kg) and had a catch surface area of 0.23 $m^2$. Twine areas were calculated for those surfaces that were at an angle to the direction of towing (i.e. do not include the parallel panels of netting in the codend or extension). Total system area is the sum of the twine, ground-chain (0.073 $m^2$), two otter boards, six sweep (0.09 $m^2$), two frame-line (0.18 $m^2$) and catch areas for each trawl. The total weight of all sweeps was 2.28 kg.
T, transversals; N, normal; B, bars.
doi:10.1371/journal.pone.0099434.t001

The LMM for drag included the fixed effects of both trawl and SOG, and so predicted means are presented at the centred value of SOG (i.e. drag at average SOGs; Table 4). There was no significant difference between the drags of the two shallow-wing trawls (FDR, $p>0.05$), but both had significantly lower drags (by 1.7–3.9%) than the three deep-wing trawls (FDR, $p<0.05$;Table 4). These differences were reflected in fuel rates and intensities that varied by up to 0.21 L $h^{-1}$ and 0.17 L $ha^{-1}$ (Table 4). Irrespective of the trawl, there was an overall positive relationship between SOG and drag (LMM, $p<0.001$).

For the biological variables, compared to the conventional 41 long deep-wing trawl, all small-meshed trawls caught significantly more commercial (by up to double) and sub-commercial (by up to almost three times) school prawns per ha trawled (Figure 3a–d); which when considered across total catches manifested as significantly smaller mean sizes of individuals (LMM and FDR, $p<0.05$; Figures 3a–e, g, 4a, Table 3). Conversely, irrespective of their wing depth, the two 32 short trawls caught significantly less total bycatch by weight per ha than the other three trawls (by between 40 and 57%; LMM and FDR, $p<0.05$; Figure 3c, Table 3). Further, compared to all trawls, the 32 short shallow-wing trawl caught significantly fewer (per ha) total bycatch (by 29–57%), southern herring (by 83–95%), and tailor (by 40–67%) by number (LMM and FDR, $p<0.05$; Figure 3d–f, Table 3). Differences in the above variables among the other trawls were less consistent (Fig. 3d–f). There were no significant differences between trawls for the number of Ramsey's perchlet per ha trawled (LMM, $p>0.05$; Fig. 3f, Table 3).

### Experiment 2: Clarence River

During 12 days of fishing, the five trawls were towed at SOGs of 1.00–2.11 $ms^{-1}$, over distances of 2.28–5.07 km. Wing-end spreads and drags were significantly different among trawls (LMMs, $p<0.001$; Tables 3 and 4). Broadly, the predicted mean (±SE) wing-end spreads were separated into three groups, with the 32 short shallow- and deep-wing trawls fishing significantly narrower (4.91±0.03 m and 4.89±0.03 m, respectively) than the 32 long shallow-wing trawl (5.08±0.03 m); which in turn was spread significantly less than both the 41- and 32 long deep-wing trawls (5.23±0.03 and 5.22±0.03 m, respectively) (FDR, $p<0.05$; Table 4).

**Table 2.** Scientific and common names and numbers of organisms caught during experiments 1 and 2.

| Group | Family | Scientific name | Common name | Experiment 1 | Experiment 2 |
|---|---|---|---|---|---|
| *Crustaceans* | Penaeidae | *Metapenaeus macleayi* | School prawn | 120 304 | 424 406 |
| | Palaemonidae | *Macrobrachium* sp. | Freshwater prawn | – | 19 |
| *Molluscs* | Loliginidae | *Uroteuthis* sp. | Squid | 44 | – |
| *Teleosts* | Ambassidae | *Ambassis jacksoniensis* | Port Jackson glassfish | 148 | 14 |
| | | *Ambassis marianus* | Ramsey's perchlet | 1 639 | 48 |
| | Anguillidae | *Anguilla australis* | Southern shortfin eel | – | 7 |
| | Apogonidae | *Siphamia roseigaster* | Pink-breasted siphonfish | 298 | – |
| | Ariidae | *Arius graeffei* | Forktail catfish | 1 | 3 008 |
| | Clupeidae | *Herklotsichthys castelnaui* | Southern herring | 1 298 | 217 |
| | | *Hyperlophus vittatus* | Whitebait | 16 | 9 |
| | Engraulidae | *Engraulis australis* | Australian anchovy | 13 | 1 |
| | Enoplosidae | *Enoplosus armatus* | Old wife | – | 1 |
| | Gerreidae | *Gerres subfasciatus* | Silver biddy | 330 | 2 |
| | Hemiramphidae | *Hyporhamphus regularis* | River garfish | 8 | – |
| | Megalopidae | *Megalops cyprinoides* | Oxeye herring | – | 2 |
| | Mugilidae | *Liza argentea* | Goldspot mullet | 31 | – |
| | | *Mugil cephalus* | Sea mullet | 9 | – |
| | Muraenesocidae | *Muraenesox bagio* | Common pike eel | – | 2 |
| | Plotosidae | *Euristhmus lepturus* | Longtail catfish | 5 | – |
| | Paralichthyidae | *Pseudorhombus arsius* | Largetooth flounder | 28 | – |
| | Percichthyidae | *Macquaria novemaculeata* | Australian bass | – | 1 |
| | Platycephalidae | *Platycephalus fuscus* | Dusky flathead | 31 | 4 |
| | Pomatomidae | *Pomatomus saltatrix* | Tailor | 4 864 | 3 |
| | Sciaenidae | *Argyrosomus japonicus* | Mulloway | 2 | – |
| | Sillaginidae | *Sillago ciliata* | Sand whiting | 64 | 2 |
| | Soleidae | *Synclidopus macleayanus* | Narrow-banded sole | – | 119 |
| | Sparidae | *Acanthopagrus australis* | Yellowfin bream | 304 | 91 |
| | | *Rhabdosargus sarba* | Tarwhine | 35 | – |
| | Tetraodontidae | *Tetractenos glaber* | Toadfish | 4 | – |
| | Tetrarogidae | *Centropogon australis* | Fortescue | – | 1 |
| | | *Notesthes robusta* | Bullrout | – | 79 |
| | Urolophidae | *Trygonoptera testacea* | Stingray | 2 | – |

–, not present in catches.
doi:10.1371/journal.pone.0099434.t002

The LMM for drag included the fixed effects of trawl, SOG and current ($p<0.001$; Table 3). The average current relative to the heading of the trawler was only 0.03 $ms^{-1}$, and so the predicted means were presented at the centred value of SOG (Table 4). The 32 short shallow-wing trawl had the significantly lowest drag (by between 9.4 and 18.4%) followed by the 32 long shallow-wing, short deep-wing and both the long deep-wing trawls (FDR, $p<0.05$; Table 4). The above differences corresponded to variations in fuel rates and intensities among trawls by up to 1.14 L $h^{-1}$ and 0.35 L $ha^{-1}$ (Table 4). Irrespective of trawl, there were overall positive relationships between drag and both SOG and current (LMM, $p<0.001$).

For catches, the four small-meshed trawls generally caught similar quantities of commercial and sub-commercial school prawns per ha trawled, and mostly significantly more than the conventional 41 long deep-wing trawl (by up to 1.4 and 1.9 times more, respectively) (LMM and FDR, $p<0.05$; Figure 5a–d, Table 3). The obvious exception was the 32 short shallow-wing trawl, which caught the same quantities of school prawns per ha across both categories as the conventional 41 long deep-wing trawl (LMM and FDR, $p>0.05$; Figure 5a–d). Combined across all catches, the mean size of school prawns retained by the 41 long deep-wing trawl was significantly larger than all small-mesh trawls (LMM and FDR, $p<0.05$); except the 32 short deep-wing trawl (Figure 4b). Compared to all other trawls, the 32 short shallow-wing trawl caught significantly less bycatch by both weight (26.25–50.42%) and number (23.60–34.01%) (LMM and FDR, $p<0.05$; Figure 5c and d, Table 3). There were no significant effects of trawl on forktail catfish numbers (LMM, $p>0.05$; Figure 5e, Table 3).

## Discussion

The results from this study further highlight the potential for improving the engineering and biological performances of penaeid trawls simply by changing their anterior mesh (1) lateral openings

**Table 3.** Summaries of likelihood ratio test (LRT) statistics from linear mixed models assessing the importance of the fixed effect of trawl (conventional 41 long deep-wing, and 32 long deep- and shallow-wing and 32 short deep- and shallow-wing trawls) in explaining variability among technical and biological responses.

| Variables | | Experiment 1 | Experiment 2 |
|---|---|---|---|
| Technical | Wing-end spread | 11.52* | 95.24*** |
| | Drag | 20.39** | 177.29*** |
| Biological | Wt of commercial school prawns ha$^{-1}$ | 21.25*** | 14.93** |
| | No. of commercial school prawns ha$^{-1}$ | 21.99*** | 17.26** |
| | Wt of sub-commercial school prawns ha$^{-1}$ | 52.28*** | 20.69*** |
| | No. of sub-commercial school prawns ha$^{-1}$ | 53.15*** | 20.92*** |
| | Mean CL of school prawns | 23.96*** | 19.43*** |
| | Wt of total bycatch ha$^{-1}$ | 33.90*** | 22.47*** |
| | No. of total bycatch ha$^{-1}$ | 42.73*** | 12.75* |
| | No. of tailor ha$^{-1}$ | 48.24*** | – |
| | No. of Ramsey's perchlet ha$^{-1}$ | 8.58 | – |
| | No. of southern herring ha$^{-1}$ | 53.60*** | – |
| | No. of fork tail catfish ha$^{-1}$ | – | 8.29 |

Excluding the mean CL of school prawns (*Metapenaeus macleayi*), all other numbers and weights were standardized to per ha trawled, calculated using the total average wing-end spread (per deployment) and then log-transformed.
–, not present in catches,*$p<0.05$, **$p<0.01$, ***$p<0.001$.
doi:10.1371/journal.pone.0099434.t003

(via different SMOs and wing twine areas) and (2) orientation angles (via different body tapers) [11,13,14,17]. By replicating the work across two experiments characterized by divergent environmental (e.g. water depth and current) and biological (e.g. different sizes of the targeted species and species assemblages) conditions, we have also provided some indication of the relative importance of such extrinsic variables on the key gear changes. The complex interaction of these variables can be discussed with respect to probable gear geometry and associated species-specific responses, and ultimately used to suggest further refinements.

Changing the mesh size, but concomitantly scaling the twine diameter, ensured that there was no appreciable difference in the twine areas of the 41 and 32 long deep-wing trawls, and both were spread using the same otter boards. Consequently, in each experiment, these trawls had almost identical wing-end spreads, drag, and therefore required similar fuel per h and ha trawled. As might be expected, the smaller-meshed trawl retained significantly smaller school prawns (although the larger-meshed trawl also lost considerable quantities of commercial-sized individuals); a trend that was maintained across clearly divergent size distributions (i.e. much smaller school prawns in Lake Wooloweyah than in the Clarence River). But, despite the much smaller mesh, the 32 long deep-wing trawl caught significantly fewer tailor (by 56%) and southern herring (by 72%), contributing to less total bycatch (by 31%) than the 41 long deep-wing trawl in the lake. The same pattern was not observed in in the river (for the only species caught in abundance—forktail catfish).

Because most of the tailor (4.0–20.0 cm TL) and southern herring (6.0–17.0 cm TL) had girths larger than the perimeter of the 32-mm mesh [15], many of the observed differences in catches may reflect either trawl avoidance completely, or potentially greater escape back through the mouth after entering. Both of

**Table 4.** Summary of predicted mean ±SE wing-end spreads (m) and drags (kgf) and subsequent estimated fuel rates and intensities for the five trawl designs tested in experiments 1 (Lake Wooloweyah) and 2 (Clarence River).

| | | 41 long deep-wing | 32 long deep-wing | 32 long shallow-wing | 32 short deep-wing | 32 short shallow-wing |
|---|---|---|---|---|---|---|
| Experiment 1 | Wing-end spread (m) | 4.29 (0.05)$^{A}$ | 4.27 (0.06)$^{A}$ | 4.40 (0.05)$^{A,B}$ | 4.31 (0.05)$^{A,B}$ | 4.47 (0.05)$^{B}$ |
| | Drag (kgf) | 256.14 (1.82)$^{B}$ | 256.89 (1.82)$^{B}$ | 248.48 (1.80)$^{A}$ | 258.57 (1.80)$^{B}$ | 251.83 (1.81)$^{A}$ |
| | Fuel rate (L h$^{-1}$) | 5.29 | 5.30 | 5.13 | 5.34 | 5.20 |
| | Fuel intensity (L ha$^{-1}$) | 2.64 | 2.66 | 2.49 | 2.65 | 2.49 |
| Experiment 2 | Wing-end spread (m) | 5.23 (0.03)$^{C}$ | 5.22 (0.03)$^{C}$ | 5.08 (0.03)$^{B}$ | 4.91 (0.03)$^{A}$ | 4.89 (0.03)$^{A}$ |
| | Drag (kgf) | 269.38 (1.57)$^{D}$ | 270.49 (1.58)$^{D}$ | 242.79 (1.61)$^{B}$ | 246.59 (1.61)$^{C}$ | 220.59 (1.65)$^{A}$ |
| | Fuel rate (L h$^{-1}$) | 6.13 | 6.16 | 5.53 | 5.61 | 5.02 |
| | Fuel intensity (L ha$^{-1}$) | 2.67 | 2.69 | 2.48 | 2.60 | 2.34 |

Mean predicted drags were derived with a centred value of speed across the ground and with zero current.
Dissimilar superscript letters for wing-end spread and drag within experiments indicate significant differences detected in false-discovery-rate pairwise comparisons ($p<0.05$).
doi:10.1371/journal.pone.0099434.t004

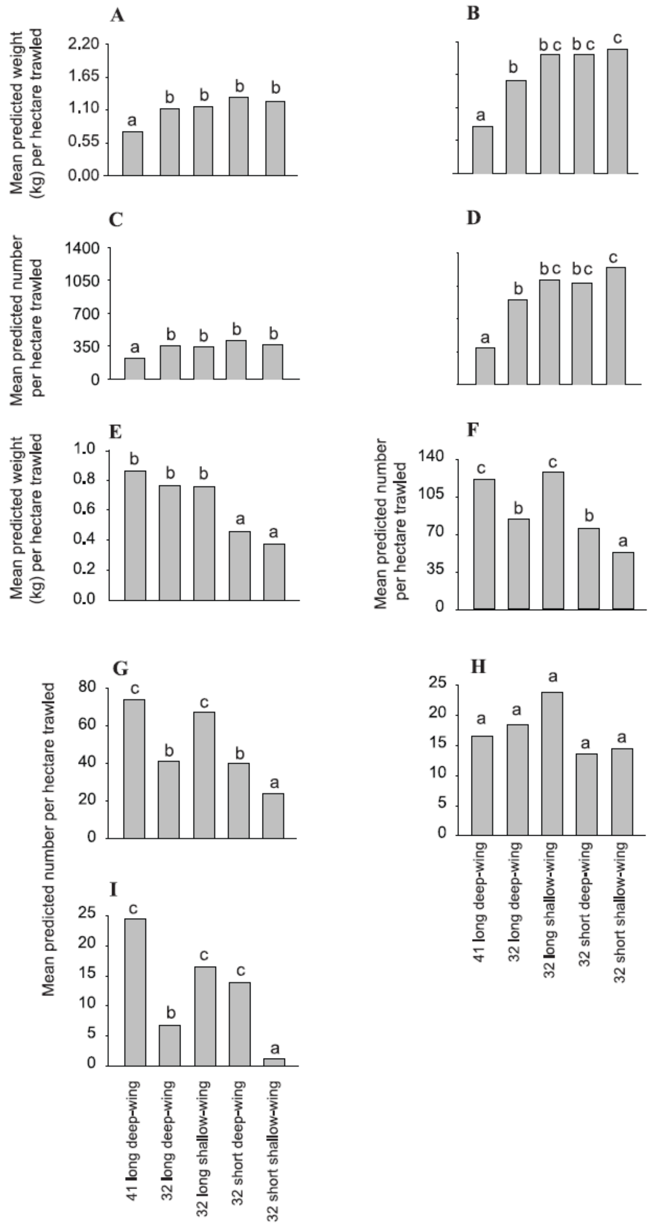


**Figure 3. Differences in predicted mean catches per ha trawled between the conventional 41 long deep-, and 32 long deep- and shallow-wing, and 32 short deep- and shallow-wing trawls used in experiment 1 (Lake Wooloweyah) for the weights of (A) commercial and (B) sub-commercial school prawns (*Metapenaeus macleayi*) numbers of (C) commercial and (D) sub-commercial school prawns, (E) weights and (F) numbers of total bycatch, and numbers of (G) tailor *Pomatomus saltatrix*, (H) Ramsey's perchlet *Ambassis marianus*, and (I) southern herring *Herklotsichthys castelnaui*.** Dissimilar letters above the histograms indicate significant differences detected in false-discovery-rate pairwise comparisons ($p<0.05$).
doi:10.1371/journal.pone.0099434.g003

these mechanisms might be attributed to the relative visibility of the trawls and/or species-specific responses to associated stimuli. More specifically, the lake was shallow (<2 m) and the relatively larger numbers of fish may have been more easily able to detect the smaller-meshed trawl and perhaps either avoid capture. By contrast, forktail catfish may have been less able to detect the approaching trawls in the much deeper river (3–18 m), although previous studies showed that this species had limited response to other anterior trawl body changes [11,13].

While not as extreme as a reduction in mesh size, varying wing depth probably also affected lateral openings in the smaller-meshed trawl bodies, although the influence on catches appeared to at least partially depend on the side taper. It is clear that steepening the side taper (in this case from 1N3B to 1N5B) causes at least two geometric changes, including (1) shortening the length of the trawl body and (2) increasing the angle of netting to the direction of tow. In terms of teleost bycatch, both effects are probably of consequence. Specifically, in an earlier study [15] we attributed bycatch reductions in other shorter trawl bodies tested in this fishery to some fish detecting the trawl and then because of the slightly reduced distance, more easily escaping (especially during haul back) [21]; either back out through the mouth (as proposed for other teleosts) [14], or through the opening at the top of the Nordmøre-grid. Similar escape mechanisms may have occurred here.

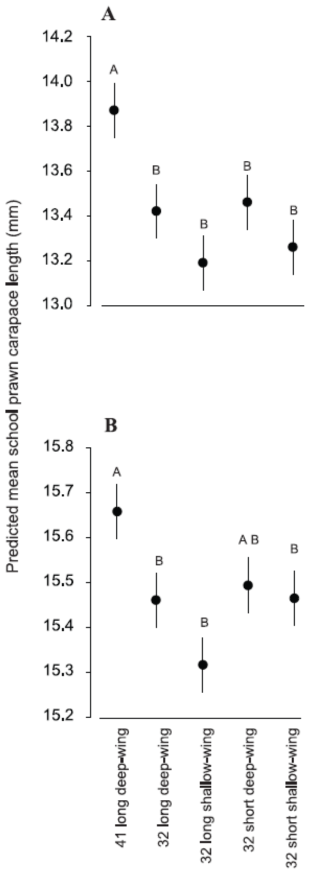


**Figure 4. Predicted mean (±SE) carapace lengths in mm retained by the five trawls in (A) experiment 1 (Lake Wooloweyah) and (B) experiment 2 (Clarence River).**
doi:10.1371/journal.pone.0099434.g004

In Lake Wooloweyah, both shorter, small-meshed trawls caught significantly less bycatch (by weight) than the longer designs, supporting the trend above, however, within side taper there were divergent effects of wing depth. In particular, the 32 long deep-wing trawl caught fewer southern herring, tailor and therefore total bycatch than the 32 long shallow-wing trawl, while the opposite relationship occurred for the 32 short trawls for these species. Such results are difficult to explain, although given there were only small variations in predicted wing end spread (e.g. <5% differences) and assuming comparable vertical fishing heights and ground gear contact, two possible effects were the relative visibilities of the trawls in the shallow lake and species-specific escape mechanisms. For example, in the 32 long deep-wing trawl, relatively more netting in the wing may have been important in terms of visibility for tailor and southern herring and promoted the avoidance of some individuals. By comparison, both the shorter 32 trawls might have already been quite visible. Reducing the depth of the wing may have more readily directed some fish toward the Nordmøre-grid−which was located relatively closer to the trawl mouth. In the absence of additional data, both of the above hypotheses are speculative. Future research would benefit from a more detailed assessment of the behavior of key species in relation to the above postulated geometric trawl changes.

The potential behavior of school prawns during capture might also explain why the 32 short shallow-wing trawl caught similar (or greater) quantities as all other small-meshed trawls in Lake Wooloweyah, but was less consistent in the Clarence River. Apart from slightly different spread wing-end spreads, the only main technical difference between experiments was the otter boards, with a solid design used in all trawls in the shallow lake, compared to a 172-mm gap used with the 32 short deep-wing trawl and an 88-mm gap with all other small-meshed trawls in the river. During previous work [12,13], we hypothesized that otter boards have a herding effect on school prawns, attributed to individuals buried in the substratum being disturbed and directed into the trawls (possibly after contacting the inner surface of the otter board). The larger gap used with the 32 short shallow-wing trawl may have allowed some school prawns to pass through the otter board after being disturbed. Any potential for such effects might be eliminated by placing mesh in the gap, although debris accumulation would increase otter-board surface area.

Irrespective of the effects on catches, reducing the twine area via less wing depth and a steeper body taper (and subsequently less otter board area in deeper water) had clear incremental impacts on drag and therefore fuel consumption. Ultimately, compared to the conventional 41 long deep-wing trawl, the 32 short shallow-wing trawl tested in the river required 18 and 12% less fuel per hour and ha trawled respectively. Based on the data presented here for the tested trawler, and assuming six hourly deployments, the fuel savings would equate to ~13 L per day during conventional fishing or up to ~1700 L per fishing season—a saving of ~$A3000.

The engineering and biological results observed here have implications for on-going research. Clearly, determining the most appropriate mesh size and ideally ensuring consistent lateral

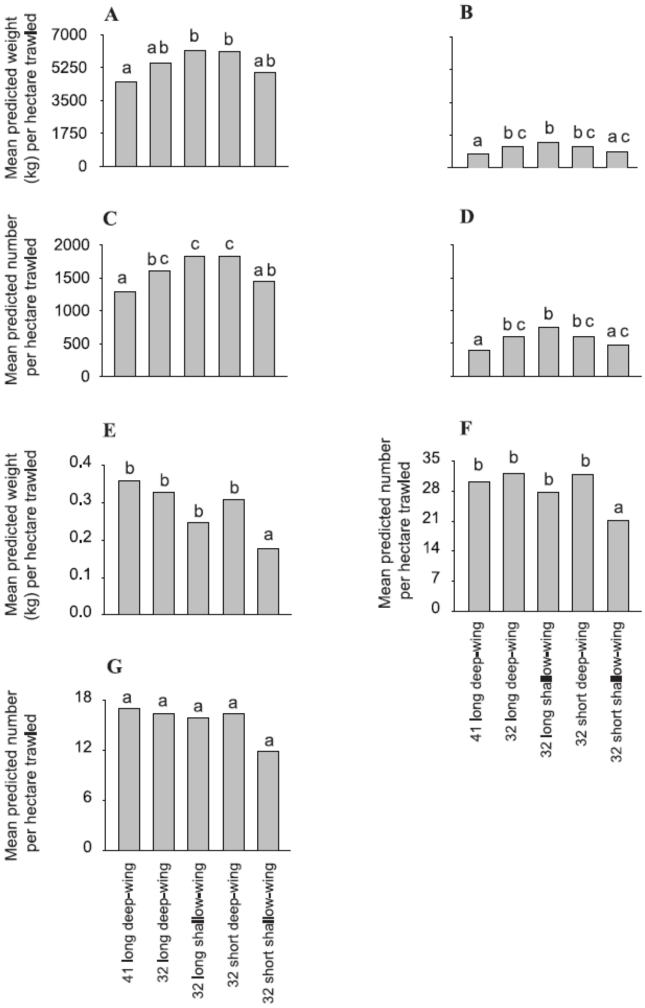


**Figure 5. Differences in predicted mean catches per ha trawled between the conventional 41 long deep-, and 32 long deep- and shallow-wing, and 32 short deep- and shallow-wing trawls used in experiment 2 (Clarence River) for the weights of (A) commercial and (B) sub-commercial school prawns *Metapenaeus macleayi*, numbers of (C) commercial and (D) sub-commercial school prawns, (E) weights and (F) numbers of total bycatch, and (G) number of forktail catfish *Arius graeffei*.** Dissimilar letters above the histograms indicate significant differences detected in false-discovery-rate pairwise comparisons ($p<0.05$).
doi:10.1371/journal.pone.0099434.g005

openings is an important precursor to other anterior gear modifications. We showed that it is possible to considerably reduce mesh size (e.g. by 22%), but still dramatically improve species selection (i.e., reduce total bycatch by up to 57%) through other changes; presumably because mesh openings mostly determined the selectivity of the targeted school prawns, whereas teleosts were more affected by changes in trawl geometry. Based on the mean sizes of school prawns retained in both experiments, the 32-mm mesh is too small. However, it should be possible to increase mesh size slightly to somewhere less than 41 mm, while still using a steep side taper to minimize teleost bycatch, and with the least amount of twine area to reduce otter-board area and drag. These results support a similar concept of attempting to optimize mesh size as a precursor to anterior penaeid-trawl changes designed to improve environmental performances in other fisheries.

## Acknowledgments

Thanks are extended to the (NSW) Professional Fishermen's Association, Steve Everson, Don Johnson, Jen Marshall, Mitch Burns, Chris Barnes, Nick Sarapuk, and especially Craig Brand for technical assistance in the field. Rob Fryer and Steve Kennelly are thanked for providing valuable comments to the manuscript.

## Author Contributions

Conceived and designed the experiments: MKB DJS RBM. Performed the experiments: MKB DJS. Analyzed the data: RBM. Contributed reagents/materials/analysis tools: MKB DJS RBM. Wrote the paper: MKB DJS RBM.

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**Appendix 15.** Broadhurst, M.K., Sterling, D.J. and Millar, R.B. 2015. Increasing lateral mesh openings in penaeid-trawl bodies to improve selection and reduce drag. Fish. Res. 170: 68–75.

Fisheries Research 170 (2015) 68–75

Contents lists available at ScienceDirect

Fisheries Research

journal homepage: www.elsevier.com/locate/fishres

# Increasing lateral mesh openings in penaeid trawls to improve selection and reduce drag

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ARTICLE INFO

*Article history:*
Received 7 August 2014
Received in revised form 6 May 2015
Accepted 18 May 2015
Handled by George A. Rose

*Keywords:*
Bycatch reduction
Drag Penaeids
Trawl selectivity

ABSTRACT

In an attempt to improve selection and engineering efficiency in an Australian penaeid fishery, the mesh size and side taper of a generic trawl design were reduced (from 41 to 35 mm) and increased (from 1N3B to 1N5B), respectively and, within the revised design, the independent and combined utility of (i) increasing the frame-line hanging ratio, and (ii) replacing the diamond-orientated wing/side panel with square-orientated mesh were investigated. Compared to the 41-mm mesh conventional trawl, all of four smaller-meshed designs (comprising either loose or tight hanging ratios, and with diamond- or square-mesh wing/side panels) had lower drag (9–12%) and required less fuel (up to 4–12%). Some of the small-meshed trawls caught fewer unwanted fish—attributed to the steeper side panels allowing individuals to swim forward and escape. Within the small-mesh trawls, there were incremental improvements in size selectivity for the targeted school prawns, *Metapenaeus macleayi* associated with both modifications. But the square-mesh wing/side panels were by far the most effective, reducing the catches of sub-commercial school prawns by up to 72%. The results support simple, retrospectively fitted alterations to existing penaeid-trawl bodies to improve selection and efficiency.


## 1. Introduction

Penaeid trawls are among the most controversial mobile fishing gears; mostly because of the small mesh sizes used (typically 30–50 mm, Vendeville, 1990), which not only create considerable drag, but also result in poor species and size selectivity (Kennelly et al., 1998). Of major concern is the potential for large collateral mortalities and subsequent negative ecological impacts to stocks of discards, and not only for the diverse assemblages of incidental fauna, but also the targeted penaeids—owing to catches of small unmarketable individuals (Broadhurst et al., 2006).

Excluding temporal and spatial closures, resolving the poor selectivity of penaeid trawls historically has involved retrospective modifications to codends—because this is where most selection is assumed to occur (Millar and Fryer, 1999). Of relevance, codends often are fairly homogenous within fleets, facilitating the fabrication and regulation of generic modifications. Typically, such modifications have involved physical bycatch reduction devices (BRDs; Broadhurst and Kennelly, 1997) or optimised lateral-mesh openings to maximise species and size selection, respectively. In terms of the latter, the methods are limited to: (i) increasing the size of the diamond-oriented mesh (e.g. Sobrino et al., 2000); (ii) reducing the codend circumference—effectively increasing the 'hanging' ratio (E; defined as the stretched length of a hanging line or operating opening of a mesh panel divided by the stretched length of the mesh panel) (e.g. Reeves et al., 1992); or (iii) changing the mesh orientation to either 90° (termed T90; e.g. Digre et al., 2010), or 45° ('T45' or more commonly, 'square mesh'; Robertson and Stewart, 1988).

Although not studied in the same detail, it has been long established that at least some species and size selection also occur in the trawl wings and body (High et al., 1969; Sumpton et al., 1989; Broadhurst et al., 2000). Intuitively, such 'anterior' escape of non-target organisms should be encouraged since this might evoke fewer mortalities. However, the difficulty with modifications to the anterior trawl is ensuring that these are not design-specific but rather, like BRDs and changes to the meshes in codends, remain applicable across trawls.

Considering the three methods for optimising lateral mesh openings described above, first testing and regulating appropriate

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http://dx.doi.org/10.1016/j.fishres.2015.05.014
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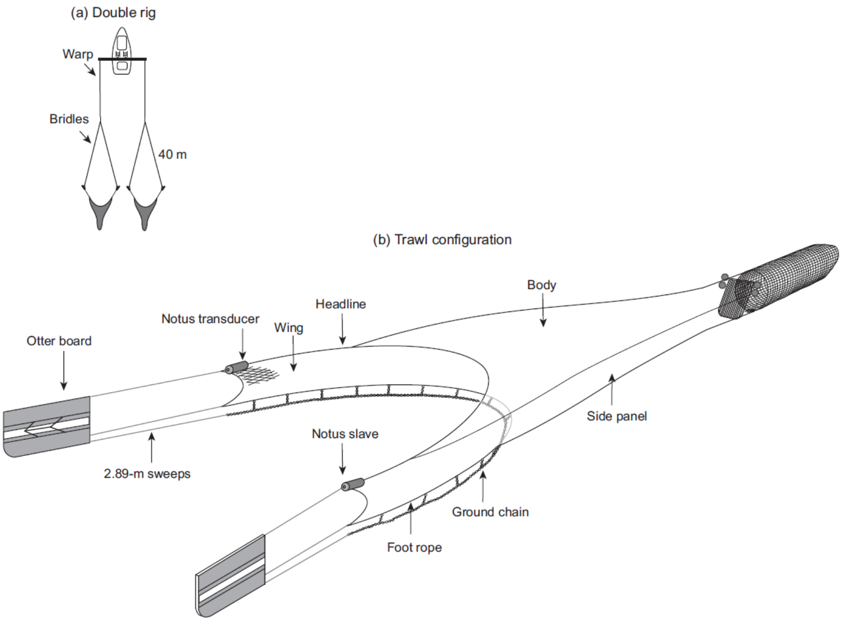


**Fig. 1.** The (a) double-rig configuration, and (b) generic otter trawl rigged with the Notus paired sensors.

fishery-specific mesh sizes is the most coherent and commonly applied strategy (Sumpton et al., 1989; Broadhurst et al., 2000, 2014). The other options of either concomitantly altering E (i.e. for the meshes at the frames lines or mouth of a trawl) or using alternative mesh orientations (throughout trawl bodies) to maintain appropriate lateral openings have been less formally investigated. Beyond the potential selectivity improvements, any reductions in twine area associated with the above three methods for optimising lateral mesh openings should also reduce trawl drag, and therefore have some measurable engineering benefits.

There is considerable variation in frame-line Es, and therefore anterior lateral-mesh openings and/or shape, among penaeid-trawl designs. Most designs, including the 'Florida flyer' and 'sandakan' have transverse (T) meshes across the bosom and clusters of mesh and bar (B) tapers that are hung across various Es; but typically >0.5 (Watson et al., 1984; with an E of 0.707 producing square-shaped meshes in the netting adjacent to the frame lines). By contrast, other designs (e.g. the 'Seibenhauser') have frame-line tapers comprising all bars across the bosom, which produces large areas of square-oriented mesh throughout the top and bottom panels.

Irrespective of the frame-line E, a simple ancillary modification to many existing penaeid trawls might be to replace sections of the side panels with T90 or T45 netting. Such netting panels have been added to other crustacean and fish trawls (typically to the top, anterior section) to exploit species-specific behavioural differences and promote the escape of unwanted organisms (Catchpole and Revill, 2008). Like in a codend, a correctly installed T90 or T45 panel in the sides of a trawl might more consistently maintain lateral-mesh openings than conventional diamond mesh.

Given the above, the aims of this study were to test the hypothesis of no effects of frame-line E across the range of coherent values, from very loose (0.550) to tight (0.707), and also altering side-panel mesh orientation (diamond- vs square-mesh) on the catching and engineering performances of a generic penaeid trawl in an Australian fishery. We chose a four-seam Florida flyer (based on the local conventional gear) as our base design, but either of the modifications described above is applicable to most penaeid-trawl designs used internationally. To illustrate the relative utility or otherwise of any such changes in the investigated fishery, in addition to the four treatments above we also included the local, conventionally rigged trawl in the study.

## 2. Materials and methods

The work was done during summer 2013/14 in the Clarence River (sandy and mud substrata in ~10–20 m depth) using a double-rigged trawler (10 m with an 89-kw engine; Fig. 1a). The trawler had 8-mm diameter (Ø) stainless warps and 40-m bridles (6-mm Ø stainless wire) on two hydraulic winches (Fig. 1a). The electronic equipment included: a fuel monitor (Floscan series 9000); global positioning system (GPS; Lowrance); attachable load cells and associated data logger (Amalgamated Instrument Company; model numbers PA6139 and TP4); a portable acoustic, trawl-monitoring system (Notus Trawlmaster System; Model no. TM800ET; Fig. 1b); and two hull-mounted sum logs (EchoPilot, Bronze Log+).

### 2.1. Trawls tested

One local, conventional trawl (included as a reference design) and four new trawls were assessed (Table 1 and Fig. 2). All trawls had four seams and the same frame-line lengths (7.35 m), ground-gear configurations (8-mm Ø stainless-steel chain), extension sections (with Nordmøre-grids installed) and codends (120 × 75 B; made from identical 27-mm mesh hung on the bar). Each trawl was attached to paired otter boards (see below) by 2.89-m sweeps with snap clips on each end (Table 1 and Fig. 1b).

**Table 1**
Technical specifications of the conventional and four small-mesh trawls. Twine areas were calculated for those surfaces that were at an angle to the direction of towing (i.e. did not include the parallel panels of netting in the codend). Total system area is the sum of the twine, ground-chain (0.15 $m^2$ for each system), otter boards, sweeps (0.18 $m^2$), frame lines (0.35 $m^2$) and catch (0.23 $m^2$) areas. Total system weight comprised the trawl body (below), codend with Nordmøre-grid (5.80 kg), otter boards (2), ground gear (10.79 kg), and sweeps (2.00 kg). T, transversals; N, normal; B, bars.

| | Conventional | Loose diamond-wing | Tight diamond-wing | Loose square-wing | Tight square-wing |
|---|---|---|---|---|---|
| Trawl | | | | | |
| Stretched mesh opening (mm) | 41.33 | 34.78 | 34.78 | 34.78 | 34.78 |
| Twine diameter (mm) | 1.20 | 0.88 | 0.88 | 0.88 | 0.88 |
| Wing end (T or B) | 75 T | 60 T | 60 T | 40 T + 20 B | 40 T + 20 B |
| Wing end (stretched length—mm) | ~3200 | ~2070 | ~2070 | ~1380 | ~1380 |
| Headline and foot-rope tapers (half trawl) | 42 AB; 7 × (IT5B, 1T4B, 1T3B, and 1T2B); and 16 T | 54 AB; 8 × (1T5B, 1T4B, 1T3B, and 1T2B) and 21 T | 54 AB; 7 × (1T5B, 1T4B, 1T3B, and 1T2B); and 20 T | 54 AB; 8 × (1T5B, 1T4B, 1T3B, and 1T2B); and 21 T | 54 AB; 7 × (1T5B, 1T4B, 1T3B, and 1T2B); and 20 T |
| Frame-line hanging ratio (E) | 0.550 | 0.550 | 0.707 | 0.550 | 0.707 |
| Wing length (N) | 70 | 83 | 76 | 83 | 76 |
| Body length (N) | 120 | 85 | 75 | 85 | 75 |
| Body/wing length (m) | ~7.90 | ~5.80 | ~5.22 | ~5.80 | ~5.22 |
| Side taper | 1N3B | 1N5B | 1N5B | 1N5B | 1N5B |
| Posterior body circumference (T or T/B) | 150 | 184 T | 184 T | 143T + 40 B | 143 T + 40 B |
| Total twine area ($m^2$) | 4.80 | 2.60 | 2.22 | 2.60 | 2.22 |
| Weight (kg) | 11.29 | 5.11 | 4.73 | 5.11 | 4.73 |
| Otter boards | | | | | |
| Individual area ($m^2$) | 0.85 | 0.71 | 0.71 | 0.71 | 0.71 |
| Individual weight (kg) | 51.90 | 50.90 | 50.90 | 50.90 | 50.90 |
| Total system | | | | | |
| Area ($m^2$) | 7.07 | 4.93 | 4.55 | 4.93 | 4.55 |
| Weight (kg) | 133.68 | 125.50 | 125.12 | 125.50 | 125.12 |

The conventional trawl (described by Broadhurst et al., 2014) was made from the legally-required, nominal 41-mm (stretched mesh opening–SMO) mesh (1.20-mm Ø twine) hung along the frame line at 0.550 E, with a wing and side taper of 1N3B and was spread by solid, flat-rectangular otter boards (1.39- × 0.61-m; Table 1 and Fig. 1b). However, because Broadhurst et al. (2014) demonstrated that modifications to increase the lateral openings of 41-mm mesh in this fishery caused large school prawns, *Metapenaeus macleayi*, to escape, the four new trawls were all made from identical, smaller nominal 35-mm (stretched mesh opening—SMO) mesh (0.88 mm diameter–Ø twisted polyethylene twine). All four new trawls had 1N5B wing and side tapers and were spread by two 1.39- × 0.61-m flat-rectangular otter boards, but with 100-mm gaps in the centre (Table 1 and Figs. 1b and 2).

The four new trawls only differed in the Es of the frame-line taper clusters ('loose' or 0.550 E vs 'tight' or 0.707 E) and the orientation of meshes in their wing/side panels (diamond vs square) (Table 1 and Fig. 2). Based on these differences, the four trawls were termed the (1) 'loose diamond-wing', (2) 'tight diamond-wing', (3) 'loose square-wing', and (4) 'tight square-wing' (Table 1 and Fig. 2).

### 2.2. Experimental design

Prior to testing, the conventional and four new trawl bodies (and other rigging) were weighed and 20 randomly-selected meshes in each were measured for SMO using a local, purpose-built mesh gauge. On each fishing day, the trawls being tested were alternately attached to the sweeps on each side of the vessel, and the Notus sensors secured at the ends of the inner and outer wings (Fig. 1b). After each trawl was deployed, the load cells were attached to the towing wires. The Notus sensors and load cells were swapped from side-to-side at the start of each day.

It was only practical to complete up to five 40-min deployments on each day, during which we assessed paired combinations of the various trawls (and their otter boards) by towing one of each pair from each side of the vessel, providing two daily replicates of each trawl on each day. Over 12 fishing days, 24 replicate deployments were completed for each trawl.

### 2.3. Data collected and statistical analyses

The technical data collected during each deployment included the: (i) drag (kgf) of each configuration; (ii) the total distance trawled (otter boards on and off the bottom—obtained from the plotter and trawl-monitoring system); (iii) speed over the ground (SOG) and through the water (STW; both in m $s^{-1}$), (iv) depth of fishing, (v) distance of the trawls behind the vessel, and (vi) the wing-end spreads (all in m). All technical data were recorded at 60-s intervals.

Biological data were collected at the end of each deployment and included the: total weights of school prawns and non-penaeid bycatch; numbers of each bycatch species; and total lengths (TL to the nearest 0.5 cm) of the most abundant teleosts. Random samples of ~750 g of school prawns were placed into plastic bags and transferred to the laboratory, where they were measured (CL in mm), weighed and counted. The latter data were used to calculate the numbers and weights of 'optimal' commercial (≥15 mm CL) and sub-commercial (<15 mm CL) school prawns during each deployment.

The hypothesis of no differences in the mesh sizes of the various trawls was tested in a linear model (LM). The remaining technical and biological data were analysed in linear mixed models (LMMs), with some standardized prior to analyses. To remove any confounding effects of slightly different wing-end spreads and distances trawled (see Results), the numbers and weights of catches were standardized to per ha trawled using the swept area of the foot rope (calculated by average wing-end spread × the distance trawled) and then log-transformed so that differences between trawls would act multiplicatively. Predicted mean numbers and weights (per ha) were obtained by back-transforming. All other data, including the school prawn mean CL per deployment, drag,

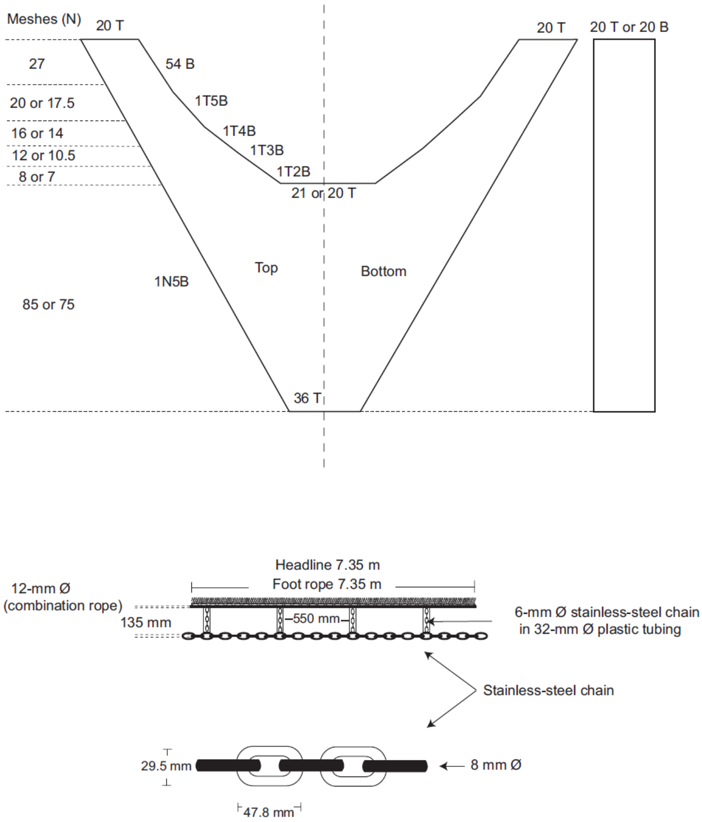


**Fig. 2.** Plan of the four small-meshed trawl bodies used. N, normal; T, transversals; B, Bars; and Ø, diameter.

wing-end spread, SOG, STW and distance trawled were analysed in their raw form.

All models included 'trawl design' as fixed, while 'trawl sides' and 'days' and the interaction between 'deployments' and days were included as random terms. For the LMM assessing drag and spread, additional random terms involved load cells and the paired Notus sensors, respectively while additional covariates included SOG, 'current' (calculated as the speed of the water in the direction of travel and defined as SOG–STW), distance aft of the trawl configuration from the vessel and fishing depth. All models were fitted using either AsReml or the lmer function from the lme4 package of the R statistical language and the significance of trawl design was determined using a Wald *F* test. Any significant differences among the four trawls were investigated using the Benjamini–Hochberg–Yekutieli procedure to control the false discovery rate (FDR; Benjamini and Yekutieli, 2001).

Predicted means from the LMMs for drag were used to calculate relative fuel consumption associated with towing the five trawls. Specifically, assuming that for any given towing speed, the concomitant fuel usage was proportional to the drag, it is possible to determine the relative fuel consumption using the predicted mean drags. Fuel consumption was standardized to per ha trawled for each design by comparing the fuel consumption rate with predicted mean wing-end spread (the rate at which area was being swept for a given trawl speed) from the relevant LMMs.

## 3. Results

During 24 replicate deployments of each trawl (total of 120 replicates), 835 and 170 kg of school prawns and non-penaeid bycatch were caught. The non-penaeid bycatch included 27 species, however ~95% comprised forktail catfish, *Arius graeffei* (44% of the catch and ranging in size from 5.0–26.0 cm TL), yellowfin bream, *Acanthopagrus australis* (20%; 6.5–22.5 cm TL), silver biddy, *Gerres subfasciatus* (18%; 2.0–16.0 cm TL) Ramsey's perchlet, *Ambassis marianus* (4%; 5.5–10.5 cm TL), large tooth flounder, *Pseudorhombus arsius* (3%; 5.5–21.0 cm TL), narrow banded sole, *Synclidopus macleayanus* (3%; 5.0–11.0 cm TL) and southern herring, *Herklotsichthys castelnaui* (3%; 5.0–17.0 cm TL). These species formed the basis of the biological analyses.

### 3.1. Engineering differences

The conventional trawl had a mean ± SE SMO of 41.33 ± 0.11 mm. There was no significant difference in the SMO among the four new trawls, with an overall mean of 34.79 ± 0.05 mm (LM, $p > 0.05$).

The five trawl designs were towed at SOGs of between 0.87 and 1.54 m s$^{-1}$, covering distances of between 2.35 and 4.17 km and with significant differences in wing-end spread and drag among trawls, and therefore ha trawled (LMMs, $p < 0.001$; Tables 2 and 3).

**Table 2**
Summaries of likelihood ratio test (LRT) statistics from linear mixed models assessing the importance of the fixed effect of trawl (conventional; loose diamond-wing; loose square-wing; tight diamond-wing; and tight square-wing trawls) in explaining variability among technical and biological responses. Excluding the mean CL of school prawns (*Metapenaeus macleayi*), all other numbers and weights were standardized to per ha trawled, calculated using the total average wing-end spread (per deployment) and then log-transformed. –, not relevant.

| Technical variables | LRT |
|---|---|
| Wing-end spread | 99.03*** |
| Hectare trawled | 6.64*** |
| Drag | 166.29*** |
| Biological variables | |
| Wt of commercial school prawns ha$^{-1}$ | 2.01 |
| No. of commercial school prawns ha$^{-1}$ | 2.92* |
| Wt of sub-commercial school prawns ha$^{-1}$ | 23.24*** |
| No. of sub-commercial school prawns ha$^{-1}$ | 23.15*** |
| Mean CL of school prawns | 20.03*** |
| Wt of non-penaeid bycatch ha$^{-1}$ | 2.95* |
| No. non-penaeid bycatch ha$^{-1}$ | 4.32** |
| No. of fork tail catfish ha$^{-1}$ | 0.36 |
| No. of yellowfin bream ha$^{-1}$ | 4.68* |
| No. of silver biddy ha$^{-1}$ | 3.02* |
| No. of Ramsey's perchlet ha$^{-1}$ | 1.08 |
| No. of narrow banded sole ha$^{-1}$ | 0.79 |
| No. of large tooth flounder ha$^{-1}$ | 0.65 |
| No. of southern herring ha$^{-1}$ | 1.14 |

* $p < 0.05$.
** $p < 0.01$.
*** $p < 0.001$.

The only appropriate fixed effect in the LMM for wing-end spread was trawl design, with all smaller-meshed trawls spread significantly less (by 2.38–5.36%) than the conventional trawl (FDR, $p < 0.05$; Table 3). Within the small-meshed trawls, the largest difference between wing-end spreads was 3.05%, with no significant differences between the diamond- or square-wing designs, nor between the two tight trawls (FDR, $p < 0.05$; Table 3).

The LMM for drag included the fixed effects of both trawl and STW, and so predicted means are presented at the centred value of STW (i.e. drag at average STW; Table 3). Compared to the conventional trawls, all small-mesh designs had significantly less drag (by up to 12.4%, FDR, $p < 0.05$; Table 3). Within the small-mesh designs, the loose diamond-wing trawls had the least drag (by 3.43%; FDR, $p < 0.05$; Table 3). Irrespective of the trawl, there was an overall negative relationship between vessel STW and drag (LMM, $p < 0.001$).

The fuel used followed a similar trend for drag, with an estimated lower rate and intensity among all four small-mesh designs than the conventional trawl (by up to 12.5%; Table 3). Within the small-meshed trawls, the loose diamond-wing was the most economical to tow, presenting a rate and intensity of up to 3.5 and 6.0% less than the others (Table 3).

### 3.2. Biological differences

Linear mixed models detected significant differences in the number of commercial school prawns ha$^{-1}$, number and weight of sub-commercial school prawns ha$^{-1}$, the mean CL across all sizes of school prawns, the number and weight of non-penaeid bycatch ha$^{-1}$, and the numbers of yellowfin bream and silver biddy ha$^{-1}$ among trawls ($p < 0.05$; Table 1; Fig. 3). False-discovery-rate paired comparisons failed to separate differences among trawls for the weight and number of commercial school prawns ha$^{-1}$, but there was a trend of greater catches in the loose and tight small-meshed diamond-wing trawls than the remaining designs (which were all similar) ($p > 0.05$; Fig. 3a and c). Both small-meshed square-wing trawls retained significantly fewer sub-commercial school prawns ha$^{-1}$ than the small-meshed diamond-wing trawls (number and weight reduced by up to 72%) and the conventional trawl (number and weight reduced by up to 54%) (FDR, $p < 0.05$; Fig. 3b and d). The escape of small school prawns from the square-wing trawls was reflected in the mean CLs, with significant incremental increases from the loose and tight diamond-wing trawls, through to the loose and tight square-wing trawls (FDR, $p < 0.05$; Fig. 4).

In terms of non-penaeid bycatch, compared to the conventional trawl, the loose diamond-wing caught a significantly lower total weight ha$^{-1}$ (by 38%) and, along with the tight diamond-wing and loose square-wing, significantly fewer total numbers ha$^{-1}$ (36, 33 and 35%; FDR, $p < 0.05$; Fig. 3e and f). The conventional trawl also caught the same quantity of yellowfin bream ha$^{-1}$ as the tight square-wing trawl, with both catching more than the loose diamond-wing trawl (by 1.6 times; FDR, $p < 0.05$; Fig. 3g). False-discovery-rate paired comparisons failed to separate the number of silver biddy ha$^{-1}$ among trawls, although both diamond-wing trawls caught fewer than the other trawls (by up to 37%; FDR, $p > 0.05$; Fig. 3h). There were no other significant differences in the catches of fish ha$^{-1}$ among trawls (LMM, $p > 0.05$; Table 1).

## 4. Discussion

This study confirms that (i) large proportions of unwanted school prawns pass through the wings and body of trawls; and (ii) such selection is strongly affected by factors other than absolute mesh size (Sumpton et al., 1989; Broadhurst et al., 2000, 2014). Ultimately, these results mean that within a given mesh size, simple modifications designed to increase and maintain lateral openings in the anterior trawl can considerably improve size selectivity. The mechanisms supporting these results can be discussed according to the probable trawl geometries and behaviour of school prawns.

The conventional trawl was included in the experiment to provide a reference point for this fishery. Despite having a considerably larger mesh size, this trawl caught more fish than most of the smaller-mesh trawls and a relatively large proportion of sub-commercial school prawns. These results can be explained by the shallower side taper, greater twine area and reduced lateral mesh openings (Broadhurst et al., 2012, 2014). Specifically, the longer body (by 1.7×) and wider netting angle (by ~7°) might have reduced the probability of small fish and school prawns contacting meshes which would have had quite narrow openings owing to the relatively greater number of meshes in the side sections. Also, because the trawl was longer, at least some fish (e.g. yellowfin bream) may have been more fatigued (during herding) and less able to escape, either from the mouth of the trawl or through the BRD.

**Table 3**
Summary of predicted mean ± SE wing-end spreads (m) and drags (kgf) and subsequent estimated fuel rates and intensities for the conventional and four new trawl designs. Mean predicted drags were derived with a centred value of speed across the ground and with zero current. Dissimilar superscripts for wing-end spread and drag indicate significant differences detected in false-discovery-rate pairwise comparisons ($p < 0.05$).

| | Conventional | Loose diamond-wing | Tight diamond-wing | Loose square-wing | Tight square-wing |
|---|---|---|---|---|---|
| Wing-end spread (m) | 5.04 (0.03)$^{A}$ | 4.92 (0.03)$^{B}$ | 4.85 (0.03)$^{B,C}$ | 4.77 (0.03)$^{D}$ | 4.79 (0.03)$^{C,D}$ |
| Drag (kgf) | 247.77 (6.70)$^{A}$ | 217.11 (6.70)$^{C}$ | 223.85 (6.71)$^{B}$ | 223.97 (6.71)$^{B}$ | 224.84 (6.70)$^{B}$ |
| Fuel rate (L h$^{-1}$) | 5.67 | 4.96 | 5.12 | 5.12 | 5.14 |
| Fuel intensity (L ha$^{-1}$) | 2.59 | 2.33 | 2.43 | 2.48 | 2.47 |

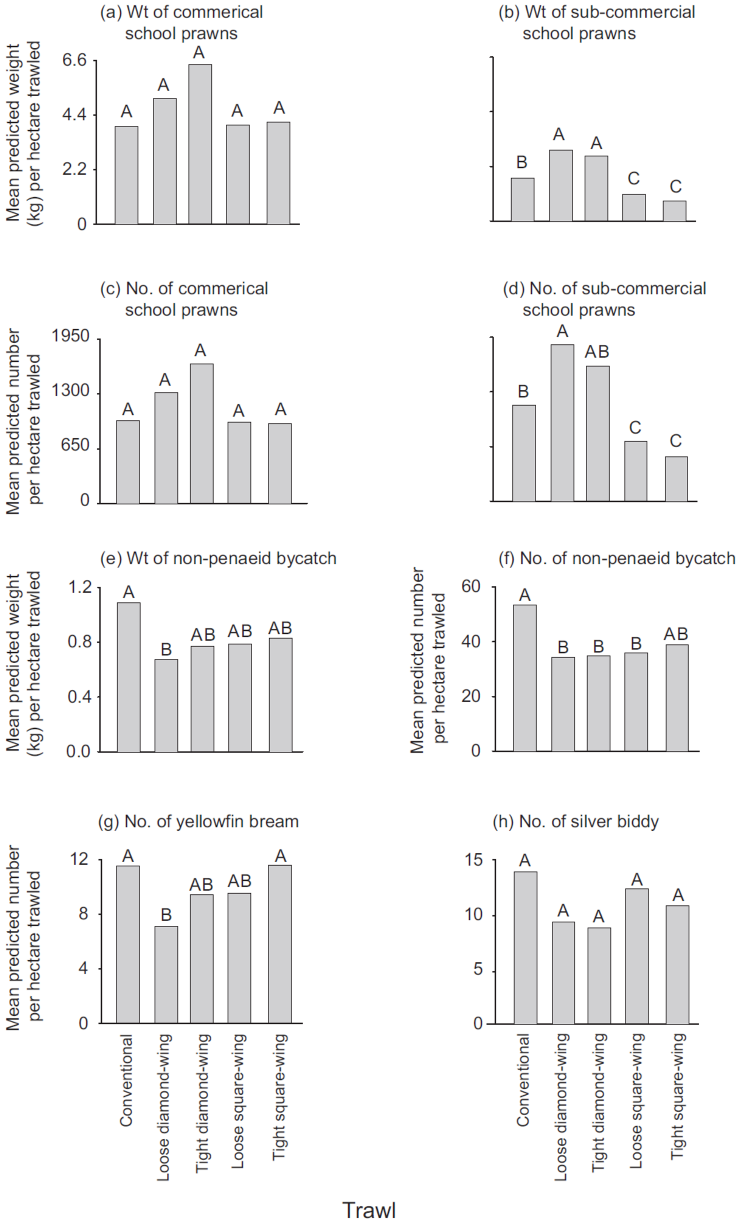


**Fig. 3.** Differences in predicted mean catches per ha trawled between the conventional, loose diamond-, tight diamond-, loose square-, and tight square-wing trawls for the weights of (a) commercial and (b) sub-commercial school prawns, *Metapenaeus macleayi* numbers of (c) commercial and (d) sub-commercial school prawns, (e) weight and (f) number of non-penaeid bycatch, and numbers of (g) yellowfin bream, *Acanthopagrus australis* and (h) silver biddy, *Gerres subfaciatus*. Dissimilar letters above the histograms indicate significant differences detected in false-discovery-rate pairwise comparisons ($p < 0.05$).

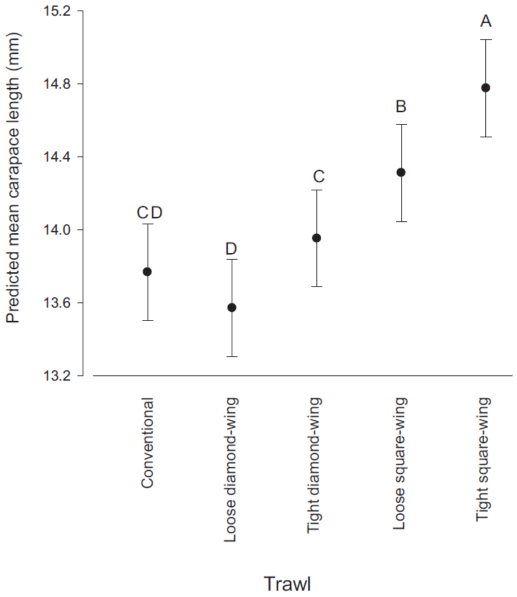


**Fig. 4.** Predicted mean (±SE) carapace lengths (mm) of school prawns, *Metapenaeus macleayi* retained by the five trawls. Dissimilar letters above the histograms indicate significant differences detected in false-discovery-rate pairwise comparisons ($p < 0.05$).

Reducing the trawl mesh size to 35 mm facilitated a steeper side taper and lower stretched wing height (and therefore a shorter length), which reduced twine area (and therefore the required otter-board area) in all small-mesh trawls, and ultimately their drag and fuel (by up to ~12% less than the conventional trawl). Beyond these broad differences however, there was substantial variation in the performances of the small-meshed trawls—affected by the two treatments of interest.

In terms of engineering performances, all small-meshed trawls offered considerable fuel savings (by up to 12.5%) over the conventional trawl. However, within the small-mesh designs compared to the loose diamond-wing trawl, there were no efficiency benefits associated with increasing E, nor replacing the diamond-mesh wing/side panel with square mesh. On the contrary, all modifications slightly reduced spread and increased drag; albeit due to potentially different causes. For example, despite having a lower twine area, the increase in drag by the tight diamond-wing trawl might have reflected the stretched mesh across the trawl mouth increasing the angle of the bars and the side panel to the direction of tow. Both effects would increase the divergence angle of the wing-end tension applied to the otter board, and increase its angle of attack (AOA) and drag. A similar mechanism (increase in otter-board AOA) might have contributed to the significant reductions in spread and greater drag of the square-wing trawls. In particular, the change in side-panel structure due to the square mesh may have reduced the tension along the sides of the trawl, increasing the effective wing angle, and ultimately the otter-board AOA. In the absence of additional data, the above hypotheses are speculative. Nevertheless, the engineering differences were minimal among the modified small-mesh trawls, and translated to marginal increases in fuel rates and intensities.

While increasing E and changing the wing/side-panel mesh orientation did not improve trawl efficiency, these modifications did dramatically affect size selectivity, and with the greatest differences due to wing/side-panel mesh orientation, although there were some incremental benefits according to complexity. Considering the likely behaviour of school prawns, the improvements in selectivity associated with the modifications provide further information on the possible key areas and mechanisms of selection in the trawl body.

Although there are no published observations of school prawns in trawls, studies of other penaeids suggests that their initial trawl contact occurs at the ground gear, after which the mostly benthic-orientated individuals contract their abdomen and are propelled according to their orientation, but typically upwards (Watson, 1989). Watson (1989) observed that after several repeated contractions (and random movements depending on orientation) penaeids were impinged against meshes in the netting panels and directed towards the codend.

Simply increasing the frame-line E from 0.55 to 0.707, significantly increased the predicted mean CL of school prawns retained. Such a modification might be expected to widen the openings of several rows of meshes behind the frame lines, and so perhaps there was some netting contact with school prawns that either moved upwards (top panel), or downwards (bottom panel), and the subsequent escape of smaller individuals. However, it is also important to consider other possible cumulative confounding effects of trawl geometry. Specifically, while the differences in spread ratio among all small mesh trawls were very low (maximum of 3%) and probably insufficient to confound trawl geometry (discussed by Broadhurst et al., 2014), the tight diamond-wing trawl was marginally shorter (12%) than the loose diamond-wing trawl. The corresponding slight difference in wing/side-panel angle may have increased the contact impact of school prawns, and their subsequent escape probability.

Maintaining the hanging ratio but including square-mesh wing/side panels achieved a much greater improvement in size selectivity. This result might reflect the greater relative area (e.g. ~16% of the total twine area) of open meshes down the sides of the trawl, where school prawns were directed towards the codend. Notwithstanding this result, combining the two modifications was the most beneficial, with a further significant increase in the mean CL. This latter result suggests a fairly random mechanism of contact by school prawns in the trawl body, which would fit the general observations for penaeid behaviour inside trawls (Watson, 1989), and may be used to support some refined direction for future modifications.

Previous studies have shown that compared to diamond-mesh codends, those made from smaller square mesh significantly increased the 50% retention length of school prawns and another penaeid (eastern king prawns, *Penaeus plebejus*) while reducing the selection range (Broadhurst et al., 2004, 2006); implying that this mesh shape is suited to penaeid morphology. The data here support this result, with the square-mesh sides facilitating the escape of small individuals and without significantly affecting catches of the targeted sizes. In fact, the predicted mean catches of the two square-mesh trawls were almost identical to the conventional trawl.

Considering the above, it might be appropriate to simply replace the diamond-mesh side-panels of conventional trawls (including the 41-mm trawls used in this fishery) with the smaller square mesh examined here. By maintaining a more appropriate lateral mesh opening, the 35-mm mesh might also facilitate a steeper side taper and shorter wing height, which would further increase the escape probability for small prawns and of equal importance reduce the overall trawl twine area, and therefore the drag and fuel.

Alternatively, given that the loose diamond-wing trawl still caught significantly more sub-commercial school prawns than the conventional trawl, it might be advantageous to examine a mesh size between 35 and 41 mm for the diamond meshes in the trawl, combined with the square-mesh sides and a steep side taper. Such modifications warrant ongoing testing since they (i) represent simple and cheap alterations that might be used to incrementally improve size selectivity, while (ii) reducing drag and fuel.

The latter outcome is particularly important, because any modification that reduces both bycatch and fuel costs without affecting targeted catches is much more likely to be adopted and refined by industries than conventional BRDs in codends. The potential utility of anterior-trawl modifications for satisfying the above criteria strongly supports their ongoing assessment as part of efforts to mitigate problematic unaccounted fishing mortalities associated with penaeid trawling.

## Acknowledgements

This study was funded by the New South Wales (NSW) Department of Primary Industries and the Australian Fisheries Research and Development Corporation (Grant no. 2011/010). Thanks are extended to the (NSW) Professional Fishing Association, Steve Everson, Don Johnson, Jen Marshall, Mitch Burns, Chris Barnes, and especially Craig Brand.

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**Appendix 16.** Broadhurst, M.K., Sterling, D.J. and Millar, R.B. 2015. Influence of diel period and cloud cover on the species selection of short and long penaeid trawls. Fish Res. 170: 144–151.

Fisheries Research 170 (2015) 144–151

Contents lists available at ScienceDirect

Fisheries Research

journal homepage: www.elsevier.com/locate/fishres

# Effects of diel period and diurnal cloud cover on the species selection of short and long penaeid trawls

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ARTICLE INFO

*Article history:*
Received 14 August 2014
Received in revised form 20 May 2015
Accepted 23 May 2015
Handling Editor George A. Rose

*Keywords:*
Bycatch reduction
Diel effects
Netting taper
Penaeids
Trawl efficiency

ABSTRACT

Diel period and diurnal cloud cover (i.e. ambient light) were tested for their importance in explaining variability in the relative selectivity of two penaeid trawls that differed only in their side tapers (1N3B or 'long' and ~28° to the tow direction vs 1N5B or 'short' and ~35°). The trawls were tested in an Australian estuarine fishery during paired deployments ($n = 44$) across replicate nights and during days with variable cloud cover (categorized as <50 and >50%). Catches were dominated by the targeted school prawns, *Metapenaeus macleayi* and seven teleosts. Only two teleosts (southern herring, *Herklotsichthys castelnaui* and Australian anchovy, *Engraulis australis*) along with the school prawns were significantly affected by trawl side taper, with all retained in lower numbers by the short trawl. For school prawns and Australian anchovy, their catch reductions mostly remained consistent irrespective of diel phase and diurnal cloud cover, but southern herring (mostly smaller individuals) only escaped from the short trawl during diurnal deployments and with <50% cloud; possibly through anterior meshes in response to more available ambient light. The results highlight the importance of environmental parameters for affecting the selectivity of penaeid trawls, and have implications for their ongoing refinement and use as survey tools.


## 1. Introduction

Penaeid-trawl fisheries are economically important for several developed and many developing countries, with more than 100 species targeted (Gillett, 2008). The life history strategies of penaeids makes them tolerant of intensive exploitation, but owing to their distribution in near shore areas characterized by diverse assemblages of small species, many penaeid-trawl fisheries are associated with disproportionate non-target catches (termed 'bycatch'; Andrew and Pepperell, 1992). Most recently, Kelleher (2005) estimated that penaeid fisheries contribute towards <1.5% of the total marine production, but >25% of global fishing discards. Historically, the mortality of such discards has raised concerns about penaeid-trawling sustainability (Andrew and Pepperell, 1992).

The simplest strategy for improving the species selectivity of penaeid trawls is to install physical 'bycatch reduction devices' (BRDs) in the codend—which can be classified according to whether they mostly separate catches via differences in (i) size ('mechanical-separating BRDs') or (ii) behaviour ('behavioural-type BRDs') (Broadhurst, 2000). Depending on the species, BRDs can reduce unwanted catches typically by >50%, and often with minimal impact on catches of the targeted penaeids (Broadhurst, 2000). Consequently, a plethora of designs have been tested or implemented in numerous fisheries, although in many cases the realized outcomes are often less than anticipated; at least partially attributed to few perceived benefits by fishers (but often additional costs and maintenance) and poor associated compliance (Cox et al., 2007).

While installing BRDs in codends is the most common technical modification for improving penaeid-trawl selection, it is clear that simply modifying the anterior trawl within existing configurations can also reduce bycatch (Sumpton et al., 1989; Conolly, 1992; Broadhurst et al., 2012, 2013a, 2013b, 2014). One inexpensive and low-maintenance modification involves steepening the wing and body tapers, and thereby shortening the trawl (Conolly, 1992; Broadhurst et al., 2012, 2014). For example, during recent work in an Australian estuarine fishery, we showed that compared to trawls with 1N3B wing and body tapers (~28° to the tow

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http://dx.doi.org/10.1016/j.fishres.2015.05.027
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direction), those with 1N5B tapers (~35°) caught fewer small school prawns, *Metapenaeus macleayi* and fish, especially southern herring, *Herklotsichthys castelnaui* (Broadhurst et al., 2014). Although speculative, these results were attributed to the steeper walls of netting having wider mesh openings and greater collision probabilities/intensities for small individuals, including school prawns. By comparison, fewer catches of larger fish might have been due to the steeper-angled netting panels more readily allowing some individuals to detect and either avoid entering the trawl or, after entering, swim forward and escape (especially during haul back; Broadhurst et al., 1996) either through meshes, from the trawl mouth, or via the mechanical-separating BRD.

Although shorter trawls showed promising results, their testing was limited to diurnal trawling (Broadhurst et al., 2012, 2014). Based on the known responses of fish, the effectiveness of modifications like short trawls for behaviourally separating some species should be strongly visual related, and therefore affected by available light and water clarity (Glass and Wardle, 1989, 1995; Wardle, 1989; Walsh and Hickey, 1993; Kim and Wardle, 1998; Gray et al., 2000). Because many penaeid-trawl fisheries operate at night and/or near shore in often turbid areas, it is important to further explore the species-specific utility of behavioural-type modifications for reducing bycatch at low light levels. It is also important to acknowledge that the poor water clarity of such areas might preclude the effective use of video as a tool for monitoring behaviour (Rakowitz et al., 2012). Rather, manipulative-type catch-comparison experiments designed to test specific hypotheses could provide more valuable information.

Given the above, our main aim was to test the hypothesis of no effects of diel or broadly variable diurnal ambient light on the relative size and species selectivities of generic penaeid trawls configured with wing and body tapers of 1N3B (long trawl) and 1N5B (short trawl) in an Australian estuary. A secondary aim was to use this information to suggest future simple anterior trawl refinements to promote more homogenous fish exclusion across various conditions.

## 2. Methods

### 2.1. Study site and vessel and trawls used

The work was done in Lake Wooloweyah (New South Wales, Australia); a shallow (<2 m) tidal barrier estuarine lagoon (sand and mud substratum and a surface area of ~25 km$^2$). The Lake is separated from the adjacent Clarence River by three relatively narrow channels, and consequently is affected by <10% of the total tidal prism making it quite turbid (Condie et al., 2012). Up to 91 small paired otter trawlers (<10 m) are permitted to fish throughout the Lake during summer (restricted to daylight hours only) targeting school prawns, with total annual catches often exceeding 140 t.

A local vessel was chartered for the experiment, with trawling done towards the end of the season (during March and April 2014) and with no other vessels on the Lake (to avoid potential confounding effects of additional noise and localized turbidity between diel periods). The vessel had two hydraulic winches, spooled with 6-mm diameter (Ø) stainless-wire bridles (always deployed to 12 m) attached to two sets of flat-rectangular, slotted otter boards (each 41.00 kg; 1.39 × 0.61 m and 0.71 m$^2$). The electronic equipment included: a global positioning system (GPS; Lowrance); a portable acoustic, trawl-monitoring system (Notus Trawlmaster System; Model no. TM800ET; Fig. 1b); and two hull-mounted sum logs (EchoPilot, Bronze Log+).

Two trawls were made from nominal 34-mm mesh (stretched mesh opening—SMO; 0.88-mm Ø twisted twine), and with identical frame-line tapers and ground-gear configurations (12-mm Ø combination foot rope attached to 135-mm, 6-mm Ø chain drops and an 8-mm Ø stainless ground chain), but different wing and body tapers (1N3B-long and 1N5B-short) and therefore lengths (~4.2 vs 3.0 m from the frame-line centre to the start of the extension section) and twine areas (3.4 vs 2.6 m$^2$) (Fig. 1). Both trawls were attached to extensions (30 N × 100 T, with Nordmøre-grids installed; Broadhurst et al., 2012) and codends (120 × 75 B; made from nominal 27-mm mesh hung on the bar).

### 2.2. Experimental design and data analyses

The long and short trawls were tested against each other in 45-min paired comparisons during six days (07:00–18:00 h) and four nights (19:15–23:00 h) either side of the new moon to maximize diel differences. The trawls were swapped from side-to-side after every second deployment, while the Notus paired sensors (located on the wing ends) were rotated at the start of every day or night.

The technical data collected during each deployment (where relevant, every 1 min) included the: (i) total distance trawled (in m; otter boards on and off the bottom); (ii) speed over the ground (SOG) and through the water (STW; both in m s$^{-1}$); and (iii) wing-end spreads (m). Cloud cover was estimated in oktas and reclassified as either > or <50%.

Catches were separated by codend, and data collected on the total weights of school prawns and bycatch, the numbers of each bycatch species, and total lengths (TL in mm) of the most abundant teleosts. Random samples of ~500 g of school prawns were placed into plastic bags and transferred to the laboratory, where they were measured (carapace length—CL in mm) weighed and counted. These latter data were used to estimate the total numbers caught and mean CL during each deployment.

The hypothesis of no differences in the SMOs of the long and short trawl bodies and their codends was tested in a linear model (LM). Wing-end spread and drag were analyzed in linear mixed models (LMMs) that included 'trawl taper' as fixed, while the random terms included 'fishing days' (encompassing either diurnal or nocturnal fishing periods), 'deployments' within fishing days, 'sides' of the vessel and the paired Notus sensors. Additional covariates included SOG and 'current' (calculated as the speed of the water in the direction of travel and defined as SOG–STW).

Excluding the mean CL of school prawns, which were analyzed raw, all catches for which there were sufficient data were first standardised for ha trawled (calculated using the known trawl opening and distance traversed) and then log-transformed so that predicted effects would be multiplicative. Two groups of LMMs were considered. The first group was applied to all catch variables, with trawl taper and 'diel phase' (diurnal or nocturnal) as fixed effects, while fishing days, deployments, and sides were random. The second group of LMMs was only applied to those variables that returned a significant main or interactive effect of trawl taper (from above) and was restricted to diurnal hauls only, with trawl taper and 'cloud cover' (dichotomous variable with < or >50% cloud cover) as fixed, and the same random factors as above.

For both LMM groups, the suite of models under consideration included the null, main effect(s) and interaction models, and also an additional model which encapsulated the hypothesis that the trawl-taper effect would only be present during daylight (group-one models) or during <50% cloud cover (group-two models). These additional models fitted an intercept term corresponding to the common nocturnal or diurnal >50% cloud effect for both tapers, and two additional effects corresponding to their diurnal or <50% cloud effects, respectively. That is, the additional models had three fixed-effects parameters; the same number as the additive main-effects model. The preferred LMMs were chosen based on forward selection with a significance level of 0.05 required to include an

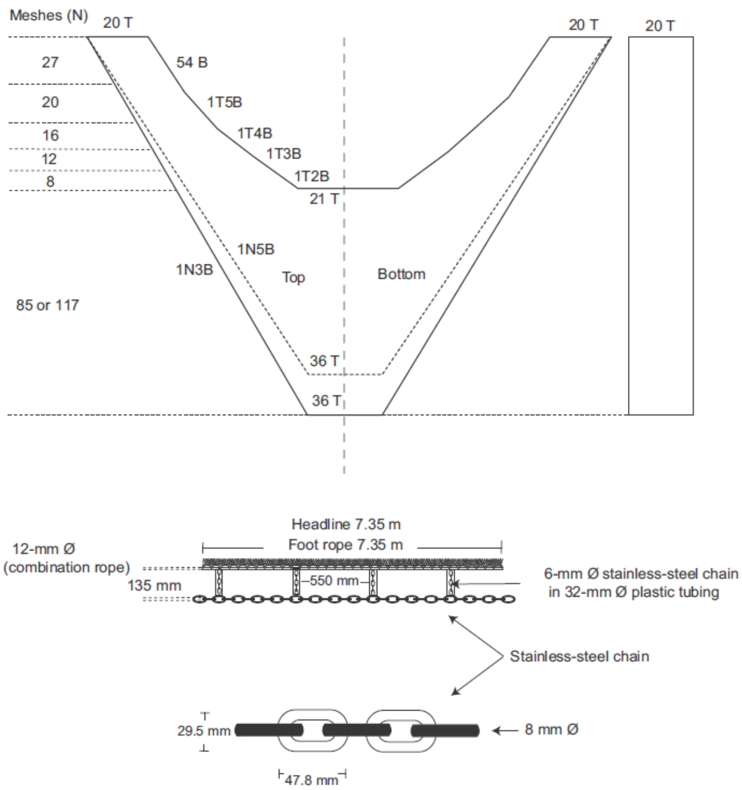


**Fig. 1.** Plan of the long (1N3B wing and body taper) and short (1N5B wing and body taper) trawls used in the study. N, normals, T, transversals; and Ø, diameter.

additional effect. All models were fitted using the lmer function from the lme4 package of the R statistical language and the significance of fixed terms was determined using a likelihood-ratio test.

## 3. Results

There was no significant difference in the SMO among the two anterior trawls, nor their codends, with overall means of 34.79 ± 0.05 and 27.37 ± 0.10 mm (LM, $p > 0.05$). The null model was accepted as parsimonious for wing-end spread (i.e. no effect of trawl taper; Table 1), although when trawl taper was included in the LMM, the predicted mean wing-end spread for the short trawl (3.82 ± 0.09 m) was slightly greater than the long trawl (3.75 ± 0.09 m)—reflecting the reduced twine area, but maintenance of otter-board area.

The total catches from both trawls comprised 1051 and 116 kg of school prawns and total bycatch, respectively. The bycatch included 31 species, although southern herring (3.5–17.5 cm TL) accounted for 55% of all fish by number, followed by forktail catfish, *Arius graeffei* (15%; 5.5–12.5 cm TL), silver biddy, *Gerres subfasciatus* (8%; 3.5–14.0 cm TL), pink-breasted siphonfish, *Siphamia roseigaster* (5%;1.5–8.0 cm TL), Ramsey's perchlet, *Ambassis marianus* (4%; 6.0–10.0 cm TL), yellowfin bream, *Acanthopagrus australis* (3%; 5.5–25.0 cm TL), white bait, *Hyperlophus vittatus* (3%; 3.0–7.5 cm TL) and Australian anchovy, *Engraulis australis* (2%; 5.0–10.0 cm TL). Excluding silver biddy (of which >50% were caught in one deployment), these species formed the basis of the catch analyses.

### 3.1. Group-one LMMs; trawl taper and diel effects

Except for the weight of total bycatch and the number of Ramsey's perchlet, all other standardised catches were significantly affected by either the main effects of (i) trawl taper and/or (ii) diel phase, or (iii) a trawl-taper diurnal-effect interaction (LMM, $p < 0.05$; Table 1 and Fig. 2). Specifically, irrespective of diel phase, compared to the long trawl, the short trawl caught significantly fewer school prawns (predicted mean weights and numbers $ha^{-1}$ reduced by 17 and 28%) across a larger mean size (13.62 ± 0.11 vs 14.02 ± 0.11 mm CL, with a difference of 0.40 ± 0.08 mm CL) and also lower numbers of Australian anchovy $ha^{-1}$ trawled (by up to 62%) (LMM, $p < 0.05$; Table 1; Fig. 2a, b, and k).

During daylight, the short trawl retained significantly fewer numbers of southern herring $ha^{-1}$ trawled (by 21%), and because of their abundance, total bycatch (by 23%) (LMM, $p < 0.05$), but both trawls had the same predicted mean catches of these variables at night (LMM, $p > 0.05$; Table 1; Fig. 2d and e). The corresponding size-frequency distributions of southern herring revealed considerably fewer individuals <8 cm TL in the short trawl during the day, and minimal nocturnal, inter-trawl differences (Fig. 3a and c). Irrespective of trawl taper, significantly more forktail catfish, pink-breasted siphonfish and yellowfin bream were caught during the

**Table 1**
Summaries of likelihood-ratio test significance for fixed effects in parsimonious linear mixed models explaining variability among key technical and biological response variables. Excluding the mean CL of school prawns (*Metapenaeus macleayi*), all other numbers and weights were standardized to per ha trawled, calculated using the total average wing-end spread (per deployment) and then log-transformed. –, not in model (i.e. not required or significant at $p = 0.05$), NA, main effect not applicable in presence of interaction. NS, not significant; * $p < 0.05$; ** $p < 0.01$; *** $p < 0.001$.

| | Diel-period main effect | Trawl-taper main effect | Trawl-taper diurnal-effect interaction |
|---|---|---|---|
| Wing-end spread (m) | – | – | – |
| Wt of school prawns ($ha^{-1}$) | – | *** | – |
| No. of school prawns ($ha^{-1}$) | – | *** | – |
| Mean CL of school prawns | – | *** | – |
| Wt of total bycatch ($ha^{-1}$) | – | – | – |
| No. of total bycatch ($ha^{-1}$) | NA | NA | ** |
| No. of southern herring ($ha^{-1}$) | NA | NA | * |
| No. of fork tail catfish ($ha^{-1}$) | *** | – | – |
| No. of pink-breasted siphonfish ($ha^{-1}$) | *** | – | – |
| No. of Ramsey's perchlet ($ha^{-1}$) | – | – | – |
| No. of yellowfin bream ($ha^{-1}$) | *** | – | – |
| No. of whitebait ($ha^{-1}$) | ** | – | – |
| No. of Australian anchovy ($ha^{-1}$) | *** | *** | – |

night than the day, while the opposite occurred for whitebait and Australian anchovy (LMM, $p < 0.01$; Table 1 and Fig. 2f, g and i–k).

### 3.2. Group-two LMMs; trawl taper and diurnal cloud effects

In total, 13 and 16 deployments (across six days) were done during >50% (75.0–100%) and <50% (12.5–37.5%) cloud cover, respectively. Irrespective of cloud cover, the short trawl consistently retained significantly fewer school prawns by weight (by 21%) and number (by 28%) and Australian anchovy $ha^{-1}$ trawled (by 49%) than did the long trawl (LMM, $p < 0.001$; Table 2 and Fig. 4a, b and e). However, for school prawns, there was a significant interaction between trawl taper and cloud cover for their sizes, with a larger difference in mean size between the short (14.28 ± 0.15 mm CL) and long trawls (13.58 ± 0.15 mm CL, with a difference of 0.70 ± 0.14 mm CL) during >50% cloud cover, than during <50% cloud cover (13.67 ± 0.14 vs 13.47 ± 0.14 mm CL, with a difference of 0.20 ± 0.13 mm CL).

There was a significant association between cloud cover and the relative numbers of southern herring and total bycatch retained $ha^{-1}$ between trawls, with 44 and 40% fewer in the short trawl during <50% cover compared to the same predicted catches in both trawls during >50% cover (LMM, $p < 0.05$; Table 2 and Fig. 4c and d). The pooled size–frequencies of southern herring revealed fewer individuals <8 cm TL in the short trawl during deployments with <50% cloud cover, and more between 12 and 14 cm TL in the presence of >50% cloud cover (Fig. 3b and d).

## 4. Discussion

This study reiterates divergent, species-specific responses to changes in penaeid-trawl wing and body tapers (Conolly, 1992; Broadhurst et al., 2012, 2014) and the importance of ambient light for affecting species and size selection (Glass and Wardle, 1989, 1995; Wardle, 1989; Walsh and Hickey, 1993; Kim and Wardle, 1998; Gray et al., 2000; Williams et al., 2011). The implications for improving penaeid-trawl selectivity can be discussed with respect to probable size and behavioural differences among the affected species.

A prerequisite to discussing the likely factors contributing towards the observed improvement in selectivity by the short trawl is to define which organisms could be physically selected through the meshes, and so postulate where selection might have occurred (Broadhurst et al., 2006). While different lateral mesh openings were probably evoked throughout both trawl bodies, it is clear from the available morphological data that the maximum mesh perimeter (69.58 mm) was sufficiently large to allow all school prawns (5–20 mm CL), along with the fusiform pink-breasted siphonfish, whitebait and Australian anchovy to pass through (Broadhurst et al., 2004; Broadhurst and Millar, 2009). By comparison, for the ventrally compressed southern herring and yellowfin bream, individuals at ~11 (Broadhurst et al., 2012) and ~6 cm TL (Broadhurst et al., 2006), respectively, would have had maximum girths the same as the mesh perimeter, and while no precise morphometric data are available for Ramsey's perchlet and forktail catfish, at least some of the smaller individuals (e.g. >7.0 cm TL) of the latter could have passed through.

Despite individuals of most species being able to penetrate meshes, only school prawns, southern herring and Australian anchovy were significantly affected by increasing taper and the implicit changes to geometry (i.e. more acute netting angles and wider lateral mesh openings). Further, based on the data here and those presented in previous studies, the reactions of the three affected species were probably somewhat divergent (Watson, 1989; Winger et al., 2010).

For school prawns, the effects of trawl taper were consistent irrespective of diel phase, however the sizes of individuals were significantly affected by available diurnal light, with the greatest difference in mean CL between trawls occurring during >50% cloud cover. Both of these observations probably reflect variation in the physical activity levels of school prawns, rather than any visual response to the trawls (Watson, 1989). Specifically, while few studies have concentrated on school prawn behaviour, penaeids in general have fairly limited responses to trawls (Watson, 1989). Most species orientate either in the substratum and typically emerge at night, although school prawns do have variable diel and diurnal catchability (Ruello, 1973; Coles, 1979; Rotherham et al., 2008); possibly influenced by location- and intra-specific differences in other important variables, including tides (Coles, 1979), substratum (Ruello, 1973), water temperature and their CL (Park and Loneragan, 1999).

Notwithstanding the above differences and irrespective of their availability to capture, Watson (1989) observed that after initial contact with the ground gear, penaeids contracted their abdomen and propelled themselves in random directions (depending on their initial orientation) leading to collisions with netting panels. This escape response was repeated several times before individuals became impinged and tumbled down the trawl body and into the codend. Assuming such behaviour was consistent among school prawns, it would explain the general, improved selection in the shorter trawl, as individuals had greater probabilities of colliding with steeper netting panels, and then passing through the potentially more open meshes. Possibly, greater school prawn activity during >50% cloud cover might account for the observed increase

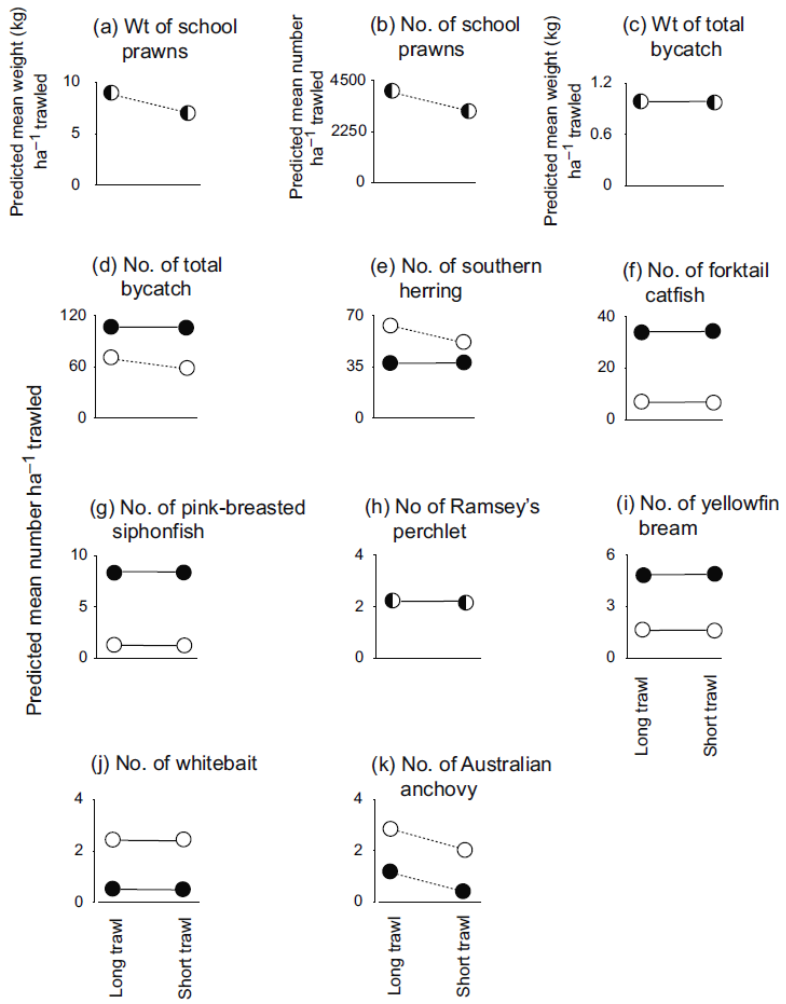


**Fig. 2.** Interaction plots of predicted mean catches ha$^{-1}$ trawled between the long (1N3B wing and body taper) and short (1N5B wing and body taper) trawls during the night (black circles) and day (open circles) for the (a) weight and (b) number of school prawns, *Metapenaeus macleayi*, weight (c) and (d) number of total bycatch and numbers of (e) southern herring, *Herklotsichtys castelnaui*, (f) forktail catfish, *Arius graeffei* (g) pink-breasted siphonfish, *Siphamia roseigaster*, (h) Ramsey's perchlet, *Ambassis marianus*, (i) yellowfin bream, *Acanthopagrus australis*, (j) whitebait, *Hyperlophus vittatus*, and (k) Australian anchovy, *Engraulis australis*. Dashed lines represent significant trawl-taper effects (LMM, $p < 0.05$).

**Table 2**
Summaries of likelihood-ratio test significance for fixed effects in linear mixed models assessing the importance of the presence (>50%) or absence (<50%) of cloud cover on diurnal variability among catches that were identified as being significantly affected by trawl taper. –, not in model (i.e. not required or significant at $p = 0.05$), NA, main effect not applicable in presence of interaction. NS, not significant; ** $p < 0.01$; *** $p < 0.001$.

| | Cloud cover (C) | Trawl-taper main effect (T) | T × C | Trawl-taper cloud-absence interaction |
|---|---|---|---|---|
| Wt of school prawns (ha$^{-1}$) | NS | *** | – | – |
| No. of school prawns (ha$^{-1}$) | NS | *** | – | – |
| Mean CL of school prawns | NA | NA | *** | – |
| No. of total bycatch (ha$^{-1}$) | NA | NA | – | ** |
| No. of southern herring (ha$^{-1}$) | NA | NA | – | *** |
| No. of Australian anchovy (ha$^{-1}$) | NA | *** | – | – |

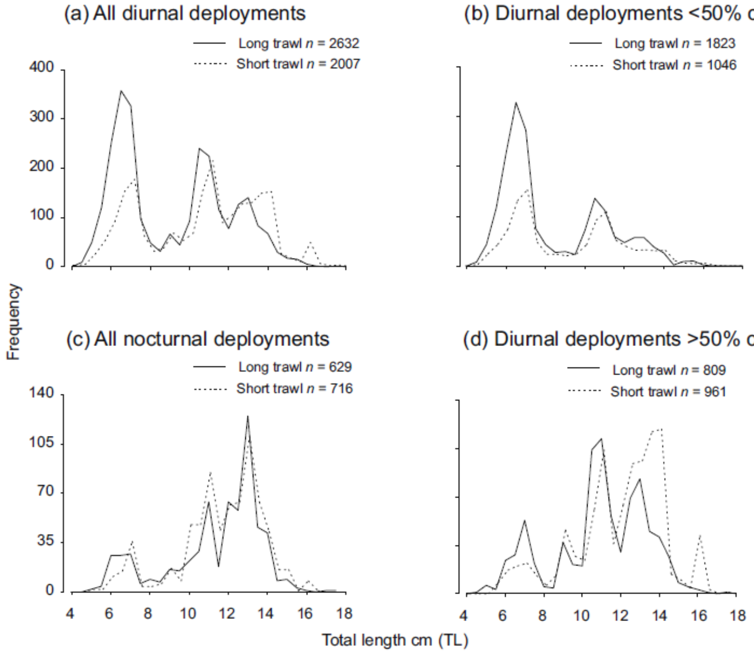


**Fig. 3.** Size–frequency distributions of southern herring, *Herklotsichtys castelnaui* retained in the long (1N3B wing and body taper) and short (1N5B) trawls for all deployments done during (a) daylight only, (b) daylight but with <50% cloud cover, (c) night only, and (d) daylight but with >50% cloud cover.

in mean size in the shorter trawls as more smaller individuals contacted meshes and escaped, although in the absence of additional data, this hypothesis remains speculative.

In contrast to school prawns, southern herring selection was significantly related to both diel phase and diurnal cloud cover, with individuals only escaping from the short trawl during sunny days. Previous studies have identified that where there is sufficient light for fish to detect trawls (>$10^{-6}$ lx; Glass and Wardle, 1989) they display a range of species-specific behavioural responses that reflect a suite of intrinsic and extrinsic characteristics, including their size, schooling behaviour and abundance, physical condition, body shape, swimming ability, learning and experience and water temperature (reviewed by Winger et al., 2010). Considering these known characteristics, one hypothesis to explain the greater escape of southern herring from the short trawl is that given sufficient ambient light, individuals were more easily able to detect the steeper panels against the background as it approached, and some therefore avoided entry, possibly under the foot rope or around the wings rather than over the headline (since the shallow water meant that the trawls mostly fished the entire water column). This species forms close schools, and so density-dependant conspecific interactions could have provided additional impetus for escape (Winger et al., 2010).

Alternatively, because many escaping southern herring were <8 cm TL (and based on their body shape were theoretically able to pass through the ~35 mm SMO), it is possible that as they were herded together towards the extension (and Nordmore-grid), the more acute difference in panel angle stimulated their penetration of anterior meshes. Similar behaviour has been observed for other teleosts in codends where there were colour/contrast changes (Winger et al., 2010). While such a theory is plausible, there was no evidence of meshing, which might be expected among fish around 11 cm TL (Broadhurst et al., 2012). More data are required to accurately determine the escape mechanism of southern herring, but it is clear that given sufficient ambient light even a slight variation in netting panel angle (~7°) and/or reduced trawl body length (~29%) are sufficient to affect their selection.

The above behavioural explanations do not extend to the only other fish (Australian anchovy) significantly affected by trawl taper. Like school prawns, Australian anchovy were consistently selected out of the short trawl, irrespective of diel phase or diurnal cloud cover. This species is quite fusiform and could easily pass through meshes across all sizes. The lack of ambient light influence suggests minimal active response and perhaps (like school prawns) more mechanical selection—possibly due to species-specific behaviour rather than swimming ability, considering the same results were not observed for whitebait (which has a similar body shape and occurred in comparable densities and TLs).

The selection of all other teleosts was not affected by trawl taper, although some of the observed diel differences may support a broader reliance on available light and therefore trawl avoidance, irrespective of design subtleties (Stoner, 1991; Kim and Wardle, 1998; Johnson et al., 2008; Rotherham et al., 2008). For example, it is possible that the relatively greater nocturnal catches of forktail catfish, pink-breasted siphon fish and yellowfin bream reflected their increased vulnerability, simply because they couldn't see either trawl. This hypothesis has been ascribed for several species in previous studies (Stoner, 1991; Johnson et al., 2008; Rotherham et al., 2008; Rakowitz et al., 2012), although the possibility for some inherent diel rhythmicity in activity among these key species could have had a confounding effect (Walsh and Hickey, 1993).

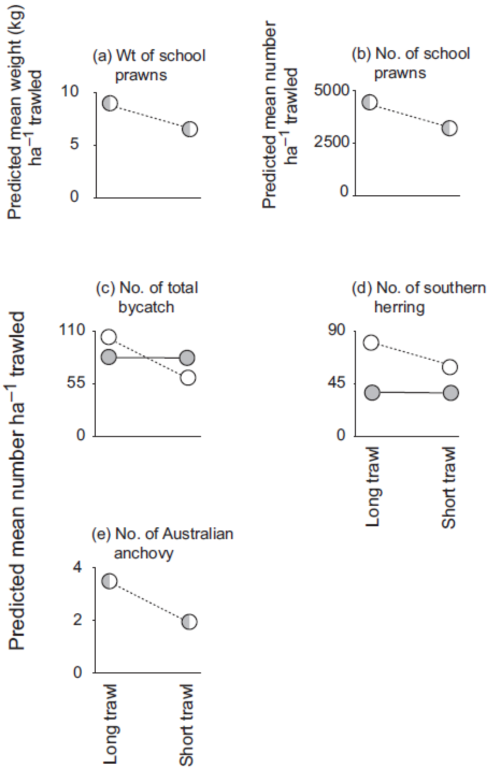


**Fig. 4.** Interaction plots of predicted mean catches ha$^{-1}$ trawled between the long (1N3B wing and body taper) and short (1N5B wing and body taper) trawls for diurnal deployments done during >50% (grey circles) and <50% (open circles) cloud cover for the (a) weight and (b) number of school prawns, *Metapenaeus macleayi*, and numbers of (c) total bycatch, (d) southern herring, *Herklotsichtys castelnaui*, and (e) Australian anchovy, *Engraulis australis*. Dashed lines represent significant trawl-taper effects (LMM, $p < 0.05$).

It is plausible that for at least some species, the observed diel differences might be a consequence of changes in spatial distributions, and more likely horizontal rather than vertical movements considering the shallow water and height of the headline. Diel variability in the distributions of estuarine fish assemblages is well established (Stoner, 1991; Johnson et al., 2008; Rotherham et al., 2008), and could reflect habitat preferences or, for the more abundant smaller nocturnal species (like forktail catfish and pink-breasted siphonfish), possibly predator evasion (Helfman, 1993). Relatively more forktail catfish, pink-breasted siphon fish and yellowfin bream may have diurnally migrated to shallower, seagrass areas in the Lake away from the sandy substratum (trawled area) and then returned to feed at night. The clear exceptions were whitebait and Australian anchovy; both of which were retained in greater numbers during the day. Stoner (1991) hypothesised that some species are adapted to high turbidity areas and therefore may not seek an advantage in terms of nocturnal feeding. A similar strategy may apply here, although some caution is required, given the low numbers.

The results from this study have important considerations for future work to improve species selection in penaeid trawls, and also for surveys that use these gears. First, differences in ambient light might explain some of the observed variability in the performances of behavioural-type BRDs tested in estuaries or turbid inshore areas, during either daylight or at night (Broadhurst and Kennelly, 1997). Second, if the key areas of escape can be identified in situ (for those species that are affected by light) it should be possible to improve responses by increasing the visual contrast of netting. Similar concepts have been applied to behavioural-type BRDs in codends (e.g. Parsons et al., 2012) and are supported by other studies examining the effects of contrasting panels to modify the visual stimulus of fish and promote their escape through meshes (Glass and Wardle, 1995; Gray et al., 2000). If any such subtle modifications can be included within existing trawl designs (and not as additional BRDs), this might facilitate their adoption. Owing to the poor water clarity that is often characteristic of penaied-trawl fisheries, research to test the above modifications would benefit from new technologies like the multibeam acoustic cameras described by Rakowitz et al. (2012) and Williams et al. (2011).

Lastly, if trawl surveys are done in estuaries where there are clear seasonal weather patterns involving extended periods of cloud cover (e.g. monsoon season in the topics), then this could potentially confound estimates of the relative abundances and distributions of some species during diurnal hauls. Conceivably seasonal latitude differences and the sun's inclination might have a similar effect on ambient light in turbid estuaries. The potential for such environmental factors to affect trawl selectivity has been identified previously for other fisheries, and warrants ongoing research (Williams et al., 2011).

## Acknowledgements

This study was funded by the New South Wales (NSW) Department of Primary Industries and the Australian Fisheries Research and Development Corporation (Grant no. 2011/010). Thanks are extended to the (NSW) Professional Fishermen's Association, Steve Everson, Don Johnson, Jen Marshall, and especially Craig Brand.

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**Appendix 17.** Broadhurst, M.K., Sterling, D.J. and Millar, R.B. 2016. Comparing conventional and new triple-rigged penaeid trawls.

Comparing conventional and new triple-rigged penaeid trawls

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## Abstract

One new and two conventional triple-rigged penaeid-trawl configurations were assessed for their relative engineering and catching efficiencies off northern New South Wales. The conventional triple rigs comprised three Florida flyers (15.20-m headline lengths) and three Seibehausers (15.31 m), while the new arrangement involved a centre Florida flyer (9.14 m), and two outside 'W trawls' (18.38-m) designed to concentrate the load centrally along bracing ropes and onto added centre sleds to produce greater spread and less overall drag. Compared to the conventional triple rigs, the tested W-trawl configuration required slightly less fuel per ha trawled, but retained substantially lower standardized catches of the targeted eastern king prawns. The relatively poorer catching performance of the new configuration was attributed to a combination of natural variability in the presence of eastern king prawns (and a requirement to test each configuration in blocks across several nights) as well as inadvertent rigging issues, which the system data indicated negatively affected the engineering performance of one of the W trawls and the catching efficiency of the other. The trials provided a solid base from which to refine the W-trawl concept for future testing.

*Keywords:* Bycatch reduction; Penaeids; Trawl efficiency

## 1. Introduction

Like most mobile fishing gears, penaeid trawls are energy intensive and, owing to their small meshes, not entirely selective for the targeted species and their sizes (Andrew and Pepperell, 1992; Keheller, 2005; Gillett, 2008, Priour, 2009). Historically, these characteristics have justified numerous attempts at trawl refinements; typically through technical modifications and mostly with respect to improving species selectivity via retroactively fitted bycatch reduction devices (BRDs) located in the codend (Broadhurst, 2000).

While BRDs are effective in reducing unwanted catches, they do not address the high energy intensity of penaeid trawls. At the broadest level, major improvements can only be achieved by reducing the drag of the key components, and more specifically, the total twine area and/or otter board area and/or angle of attack (AOA; Sterling and Eayrs, 2010). Ideally, any modifications to either of these key components would also positively affect species or size selectivity, or at least maintain the catch status quo (Broadhurst et al., 2013a; b).

There are several options for reducing the twine area of trawls, including using configurations with the same cumulative headline length, but more smaller trawls (triple- and quad-rigs) than larger fewer trawls (single- and double-rigs) (Broadhurst et al., 2013b); shorter trawl bodies (through steeper side tapers; Conolly, 1992); greater hanging ratios at the frame lines (Broadhurst et al. 2014a); narrower twine diameters (Sumpton et al., 1989); lower wing heights (Broadhurst et al. 2014b); and square-mesh panels (Broadhurst et al., 2014a). Many of the above changes can be made within existing trawl designs, but there also exists substantial variability in key parameters among conventionally used designs (Watson et al., 1984). A sensible first step in attempting to refine any particular penaeid-trawling system might be to assess the inherent variability among the range of existing designs.

Two commonly used trawl designs used over the history of penaeid-trawling in Australia that represent the wider ranges of some of the variability above are the ‘Florida Flyer’ and ‘Seibenhauser’ (Fig. 1). The Florida Flyer has transverse (T) meshes across the bosom and clusters of mesh (transversal direction−T) and bar (B) tapers (Fig. 1a). By contrast, the Seibenhauser has frame-line tapers comprising all bars across the bosom, which produce large areas of square-shaped mesh throughout the top and bottom panels, and has less twine area for the same headline length due to a very steep side taper—which theoretically should translate to relatively lower towing force (Fig. 1b).

Another broad penaeid-trawl design less commonly used in Australia is the so-called ‘tongue’ trawl, which might be configured to minimise drag (while still maintaining headline length) via an alternative rigging arrangement rather than less twine area (Watson et al., 1984). Specifically, such designs have an additional bridle wire from the headline centre, effectively reducing the required spreading force, and therefore the otter-board size (Figs 2a and 3). A tongue-trawl design might be more suited to single-or double-rigged penaeid systems, but can be fished in a triple rig with a more conventional design as the centre trawl (Figs 2 and 3a). One prototype tongue trawl recently developed at the Australian Maritime College in Tasmania, is a so-called ‘W’ trawl, comprising both upper and lower tongues (Balash et al., 2015; Figs 2a and 3a).

While all three trawl designs above encompass varying aspects that are thought to affect drag, there are no formal comparative trials assessing overall performances (against some standardised catch-per-energy indicator). Such information is not only required to assess the potential benefits of optimising environmental performances simply within existing designs, but it is also a necessary precursor to establishing a performance base-line for ongoing development/refinement. Considering the above, our aims in this experiment were to test the hypothesis of no differences in the engineering and catching performances of triple-rigged Florida Flyer and Seibenhauser trawls, and a combination of two outside W trawls and a centre Florida Flyer; all with the same cumulative headline length (~46 m).

## 2. Methods

### *2.1 Vessel and equipment*

The experiment was completed over twelve nights during February 2014 off Yamba, NSW (29$^o$ 26'S; 153$^o$ 22'E), using a local, triple-rigged trawler (16.40 m and 224 kw) fishing in 33–100 m across sandy substrata. The trawler had 10-mm diameter (Ø) galvanized-steel warps and bridles on two hydraulic winches. On-board electronic equipment included: a fuel monitor (Floscan series 9000); global positioning system (GPS; Lowrance); two hull-mounted sum logs (EchoPilot, Bronze Log+); attachable warp load cells and associated data logger (Amalgamated Instrument Company; model nos PA6139 and TP4); and a trawl-spread monitoring system (Notus Trawlmaster System; Model no. TM800ET). The latter comprised a computer processing unit, vessel-mounted omnidirectional hydrophone (located adjacent to the vessel winches), and two cylindrical transducers and associated slaves (each 330-mm long × 77-mm Ø; 1.1 kg in water); all designed to be mounted onto the wing-ends of the centre and each of the outside trawls (Fig. 3).

### *2.2. Trawl configurations and testing*

Three sets of triple-rigged trawls were fished, including: 3 × identical Florida Flyers (15.20-m headline length and 18.62 m$^2$); 3 × identical Seibenhausers (15.31-m headline length and 12.77 m$^2$); and 2 × Ws (18.38-m headline lengths and 20.52 m$^2$) with a Florida Flyer (9.14-m headline length and 4.09 m$^2$) for use as a centre net (Figs 1−3). All trawls were made from identical 48-mm stretched mesh opening (SMO; 1.68-mm Ø polyethylene−PE twine) mesh and had the same ground-gear configurations (10-mm Ø combination foot rope attached to 135-mm, 6-mm chain drops and an 8-mm stainless-steel ground chain) (Fig. 3). All trawls were attached to identical codends (150 T × 24 N of 42-mm SMO and 1.20 mm Ø braided PE twine) and extension sections (100 T × 75 N of 46 mm SMO and 1.20 mm twisted Ø PE twine) with composite square-mesh panel BRDs installed (Broadhurst and Kennelly, 1997). The same three codends were rotated among configurations using zippers (Buraschi S146R, 2.00 m long).

Two pairs of flat-rectangular otter boards (2.34 × 0.86 m; 120 kg each and 1.83 × 0.70 m; 130 kg each) and three pairs of sleds (1.98 × 0.86 m, 300 kg; 1.55 × 0.96 m, 150 kg; and 1.35 X 0.99 m, 160 kg) were used in the experiments. The larger otter boards were used with the Florida-flyer and Seibenhauser trawls, while the smaller pair was used with the W-trawl configuration along with both pairs of lighter sleds. The smaller otter boards had headline attachment points welded at the upper training edge to ensure a consistent vertical trawl opening and the lighter sleds had headline connections below the top (all at 0.86 m). The heavier of the two light sled pairs was used at the centre of the W trawls, while the other pair was located between the W trawls and the centre Florida-flyer.

At the start of each night the vessel was rigged with one of the three triple-rig treatments and appropriate otter boards. A Notus transducer and slave pair was secured to the inner and outer wing ends of one side trawl and the outer wing ends of the centre and other side trawl (Fig. 3). The triple rig was deployed for five 120-min (or thereabouts) deployments on each night. Over nine nights, we completed three alternate nights of each configuration, providing 15 replicate deployments.

### *2.3. Data collected and analyses*

The technical data collected during each deployment included the: (i) drag of each configuration (kgf); (ii) total fuel consumed per deployment (L; period between otter boards on and off the bottom); (iii) the total distance trawled (m; otter boards on and off the bottom – obtained from the plotter and net monitoring system); (iv) speed across the ground (SOG) and through the water (STW; both in m

$s^{-1}$) (v) depth of fishing (m); (vi) distance of the trawls behind the vessel (m); and (vii) the wing-end spreads (m). Drag, speed and wing-end spread were recorded at 1-min intervals.

The combined wing-end spreads for the side and centre trawls (where relevant) were calculated after adjusting for the span of the sleds and sweeps. Predicted wing-end spreads were used to calculate otter-board AOA (from the model proposed by Sterling, 2005).

At the end of each deployment, the catches from each of the three trawls (in each configuration) were separated into total king prawns, by-product and bycatch and each weighed. Catches within these three categories from each trawl were then combined, and the total numbers of each bycatch (via sub sampling) and by-product species, and total lengths (TL in mm) of the most abundant teleosts recorded (i.e. from the total catch). Random samples of ~50 eastern king prawns from the total catch in each deployment were measured (carapace length – CL in mm) and weighed. These latter data were used to estimate the total number and mean CL caught from each triple-rig configuration during each deployment.

The technical and biological data were analysed in linear mixed models (LMM), with some standardized prior to analyses. The total weights of eastern king prawns, *Penaeus plebejus* by-product and bycatch from each of the three trawls within each triple-rig configuration were standardised to per ha trawled using the swept area between the wing-ends multiplied by the distance trawled and then log-transformed. Data for individual species (pooled across trawls) were treated as above, but standardised to per ha trawled using the cumulative (total) wing-end spread of the three trawls. The remaining data (including mean CL, drag, wing-end spread, SOG, distance and ha trawled, and fuel consumed) were analysed in their raw form.

Linear mixed models were fitted to explain variability among responses describing the performance of triple-rig configurations (i) within (i.e. for total king prawns, by-product and bycatch) and (ii) across trawls (i.e. for all other data). Relevant LMMs included 'trawl configuration' and, where appropriate, 'trawls' and their interaction as fixed, while nights were included as random terms. In an attempt to more closely explain variability among cumulative wing-end spread, drag, and fuel consumption, additional covariates, including SOG, 'flow' (calculated as the speed of the current in the direction of travel and defined as SOG–STW), distance aft of the trawls from the vessel and fishing depth were also included.

All models were fitted using the lmer function from the lme4 package of the R statistical language and the significance of trawl configuration determined using a Wald F. Where competing models were assessed, the most parsimonious was chosen based on the lowest value for a penalised log-likelihood in the form of Akaike's Information Criterion. Significant differences detected for the main effects were subsequently explored using pairwise comparisons in conjunction with the Benjamini–Hochberg–Yekutieli procedure to control the false discovery rate (FDR).

## 3. Results

During 12 nights of fishing, we successfully completed 16 replicate deployments for each of the Florida-flyer and Seibenhauser configurations and 15 replicates of the W-trawl configuration, with an average of 135 ± 0.89 mins. Total catches from the 47 deployments included 1228, 5945and 2034 kg of eastern king prawns, by-product and bycatch, respectively and were representative of conventional fishing. The by-product and bycatch comprised 22 and >25 species, with 16 caught in sufficient quantities to enable meaningful analyses (Table 1). Based on sizes, some species had individuals comprising both bycatch and by-product (Table 1).

### *3.1 Engineering performances*

The trawls were towed across average (±SE) SOGs, depths and distances of 1.24 ± 0.02 m $s^{-1}$, 53.16 ± 1.46 m and 10.11 ± 1.44 km, respectively. The parsimonious LMMs describing SR for the port (which ranged from 0.60 to 0.69), centre (0.68−0.80) and starboard trawls (0.60−0.79), and the total system (0.62−0.75) comprised the significant main effects of trawl configuration and depth ($P < 0.05$; Table 1). For the main effect of trawl configuration (and irrespective of depths), there were consistent, incrementally lower SRs for the side and centre trawls and total system from the W-trawl; Seibenhauser and Florida-flyer configurations (FDR, $P < 0.05$; Tables 1 and 3, Figure 4). Within configurations, the centre trawls all had greater SRs than their outside trawls, which were generally similar except for the W-trawl configuration (the starboard trawl was spread considerably wider than the port; Fig. 4). The differences in total SR manifested as significant variations in hectare trawled among configurations (LMM, $P < 0.001$; Tables 1 and 2).

There were no significant differences in SOG, nor the fuel per hour (rate) among configurations (LMM, $P < 0.01$), with both parsimonious LMMs reduced to the fixed effect of current (LMM, $P < 0.01$; Tables 1 and 2). Similarly, drag remained the same among configurations, and was best described by the null model (LMM, $p > 0.05$; Tables 1 and 2).

By comparison, the LMM for fuel ha trawled (intensity) included SOG (negative relationship) and trawl configuration; both of which were significant ($P > 0.05$; Tables 1 and 2). False discovery rate pairwise comparisons among the three trawl configurations revealed that the W-trawl had a significantly lower intensity (5.33 ± 0.45 L $ha^{-1}$) than the Seibenhauser (5.57 ± 0.46 L $ha^{-1}$) ($P < 0.05$) but not the Florida-flyer configuration (5.53 ± 0.45 L $ha^{-1}$) ($P > 0.05$; Table 2). The latter two configurations did not have significantly different intensities ($P > 0.05$; Table 2).

*3.1 Catching performances*

There were significant differences in the catches of total eastern king prawns, bycatch and by-product $ha^{-1}$ retained in the port and starboard trawls among configurations (LMM, $P < 0.05$), but not the centre trawls ($P > 0.05$; Tables 1 and 2, Fig. 5). The differences among side trawls were sufficient to cause significant variation among the total system weights and numbers of eastern king prawns and weights of bycatch $ha^{-1}$ (FDR, $P < 0.05$; Table 1, Fig. 5a and c) but not by-product ($P > 0.05$; Table 1, Fig. 5b).

False-discovery-rate pairwise tests revealed that compared to the port and starboard trawls in the Florida-flyer configuration, both W trawls caught significantly less eastern king prawns (by up to 55%), by-product (by up to 66%), and bycatch (by up to 64%), while the port and starboard Seibenhausers caught significantly less bycatch (than the Florida flyer—by 29%; $P < 0.05$; Fig. 5). The starboard W trawl also caught significantly fewer of the above variables than the starboard Seibenhauser (FDR, $P < 0.05$), however these differences were not maintained in the port trawls (FDR, $P > 0.05$, Fig. 5). In terms of total system catches, the W-trawl configuration caught significantly less eastern king prawns (by 45%) and bycatch (40%) than the Florida-flyer, and while not significant, less than the Seibenhauser (by 30 and 17%, respectively; FDR, $P > 0.05$; Table 1). Further, the Seibehauser configuration retained significantly less bycatch (by 27%; FDR, $P < 0.05$) than the Florida-flyer configuration, and although there was no significant difference in the catches of eastern king prawns, the Seibenhausers caught 19% less (FDR, $P > 0.05$, Table 1). There was no significant differences in the mean sizes of eastern king prawns among configurations, although the Florida-flyer configuration retained a slightly smaller mean size (39.05 ± 2.53 mm CL) than the Seibehauser (41.25 ± 2.53 mm CL) and the W-trawl configurations (43.23 ± 2.53 mm CL) (LMM, $P > 0.05$; Table 1).

The only other catches significantly affected by trawl configuration were the total system numbers and weights of retained red mullet *Upeneichthys lineatus* and discarded long-spine flathead, *Platycephalus longispinis* $ha^{-1}$ trawled (LMM, $P < 0.05$; Table 1, Fig. 6). False discovery rate pairwise comparisons revealed that the W-trawl and Seibehauser configurations similarly caught significantly fewer of these species than the Florida-flyer configuration ($P< 0.05$; by up to 94%; Fig. 6).

## 4. Discussion

This study represents one of the few attempts at comparing the relative engineering and catching performances of conventional and modified penaeid-trawl configurations (Watson et al., 1984; Broadhurst et al., 2012, 2013a,b) and especially within a triple rig. The observed differences among the three configurations assessed here can be discussed by first considering the temporal sampling protocol (e.g. mostly with respect to catching efficiencies) and then vagaries among some of the operational configurations (i.e. for the W-trawl configuration) and lastly the intended, inherent design differences. Ultimately, the results can be used to promote future refinements among triple-rig systems.

Prior to discussing the relative engineering and catching performances of the three configurations, the experimental design warrants consideration for some confounding effects. In particular, logistics dictated it was impossible (i.e. too dangerous) to change treatments within nights at sea; effectively precluding full assessment of the likely important random effects of within- and between-night variability. Rather, each treatment was tested in two-day blocks and, owing to additional logistic constraints (including satisfying the skipper's requirements) this meant that for the W-trawl configuration all four nights were consecutive (i.e. no other treatment used in between).

By chance, the Florida-flyer and Seibenhauser configurations were tested during mostly good sea conditions and with minimal or no moon light (i.e. during the new and first and last quarter moons); conditions considered the most amenable for maximizing catches of the targeted eastern king prawns. Conversely, the W-trawl was tested across nights with comparatively longer periods of moon light (mostly full moon) and for some nights, poorer weather (i.e. relatively greater wind and sea states). Both conditions at least partially contributed towards the relatively poor catching performance of the W-trawl configuration (supported by similar poor performance from adjacent vessels fishing on the same nights), while the adverse weather (e.g. waves and wind) would have masked finer-scale assessments of some engineering differences.

Beyond the potential for confounding effects of the experimental design, there were also some issues associated with the rigging of the W-trawl configuration which affected its SR and optimal fishing configuration. Specifically, LMMs indicated a significant difference in SR among configurations that was largely driven by large values for the starboard and centre trawls of the W-trawl configuration, which contributed towards an average across the gear of 0.73 (vs 0.66 and 0.63 for the Florida flyer and Seibenhauser). Such values were expected, since the W trawl is designed to have a high SR to capitalise on the fact that it is relatively easier to spread (owing to the load distributed along the centre line; Balash et al., 2015). But, it was clear that the port W trawl was below the design SR, and probably because of some stretching of the bracing ropes. The port trawl was built first and tested on a different vessel during earlier trials, and whilst we knew the bracing ropes had stretched, we were unaware that this had occurred to an extent where they required replacement. The stretched bracing ropes would have negatively affected the engineering characteristics of the entire configuration.

Notwithstanding the above, the W-trawl configuration required the least amount of fuel per ha trawled than the other configurations, and significantly less than the Seibnenhauser. Although not significant, the latter trawl system also had the lowest drag. The reduction in drag by the Seibehauser was a lot less than the difference in netting area, but this result can be explained by concomitant engineering implications of the designs. Specifically, the Seibenhauser had the lowest SR, indicating it was harder to spread even if it had low netting drag. This result might be explained by a relatively greater wing-end angle associated with such a short trawl and steeper side sections. These greater angles tend to evoke a larger AOA on otter boards (in contradiction with the estimates of AOA provided, which assume all trawls have the same wing-end angle vs SR relationship) and therefore greater otter-board drag. Also, if the Seibenhauser had less netting drag, this would produce less uppull on ground chains and centre sleds—causing all of these components to have greater seabed interactions and drag.

The inherent design features of the Seibiehauser and W-trawl might also explain some of their relatively lower catches of eastern king prawns and also bycatches (i.e. mostly comprising small fish). Both configurations had steeper side tapers (especially the Seibehauser) than the Florida flyers, which would have increased the probability of organisms making contact with netting panels and possibly escaping. In support of this hypothesis, and although not significant, both the Seibehauser and W-trawl configuration retained eastern king prawns at a slightly larger mean size than the Florida flyer.

However, any inherent geometric differences are unlikely to completely account for the dramatic reduction in catches of eastern king prawns per ha trawled by the W-trawl configuration. We suggest that most of these reductions were due to the confounding effects of temporal effort (and the associated moon phases and weather discussed above). In support of this hypothesis, there were no differences in catches per ha of other crustaceans (e.g. smooth bugs, *Ibacus chacei* or blue swimmer crabs, *Portunus pelagicus*), nor cephalopods or larger fish (by-product). The only other species affected by the W-trawl configuration (and also by the Seibenhauser) were red mullet and long-spine flathead. Both species are relatively fusiform and could have passed through the steeper, more open meshes in the bodies of these trawls.

The potential for confounding effects in this study detract from the performance of the W-trawl system. During preliminary work, Balash et al. (2015) proposed that by redirecting the drag to the centre-line, the W trawls should provide drag savings of up to 20% over conventional trawls with the same headline within a double rig. While the same extent of drag savings may not be realised for triple rig (owing to the inherent efficiency of this configuration), one might expect further improvements to the relative fuel intensity reductions observed here. Obviously any such W trawls would also need to maintain catches of targeted species, but these results serve to illustrate some of the possible benefits and justify ongoing testing of the new system.

Within existing conventional trawls, coherent modifications might simply involve minimising twine area via thinner, durable twine and/or knotless netting; both of which might offer practical benefits without compromising the catching performance of proven designs, although ideally, any modifications would serve to not only reduce drag, but also unwanted catches. Additional research is warranted to explore the potential for such modifications, because fuel costs and unaccounted fishing mortality (through poor selection) are likely to remain contentious issues for penaeid trawling into the future (Gillett, 2008; Priour, 2009).


## Acknowledgements

This study was funded by the New South Wales (NSW) Department of Primary Industries and the Australian Fisheries Research and Development Corporation (Grant no. 2011/010). Thanks are extended to the (NSW) Professional Fishermen's Association, Steve Everson, Don Johnson, Jen Marshall, and especially Craig Brand.


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**Table 1.** Summaries of fixed effects in linear mixed models (LMM), and likelihood ratio tests (LRT) assessing the significance of trawl configuration for technical and biological variables. Linear mixed models for biological variables considered trawl configuration, days and deployments as potential explanatory variables, while those for technical variables also considered speed over the ground (SOG) and current (where relevant). Numbers and weights were standardized to per ha trawled, calculated using the wing-end spread (per deployment) of either the side trawls, centre trawl or total system (all trawls combined) and then log-transformed before analyses. − ret., retained; disc., discarded; EBSF = eastern blue-spotted flathead.

| | Significant fixed effects in LMM | LRT for trawl configuration |
|---|---|---|
| Technical variables | | |
| Port trawl spread ratio | Trawl configuration and depth | 35.01*** |
| Centre trawl spread ratio | Trawl configuration and depth | 51.82*** |
| Starboard trawl spread ratio | Trawl configuration and depth | 362.00*** |
| Total system spread ratio | Trawl configuration and depth | 108.40*** |
| Speed over the ground (m $s^{-1}$) | Current | ns |
| Hectare trawled | Trawl configuration and depth | 22*** |
| Drag | | ns |
| Fuel rate (L $h^{-1}$) | Current | ns |
| Fuel intensity (L $ha^{-1}$) | Trawl configuration and SOG | 6.65* |
| | | |
| Biological variables | | |
| Wt of eastern king prawns, *Penaeus plebejus* $ha^{-1}$ port trawl | Trawl configuration | 8.02* |
| Wt of eastern king prawns, $ha^{-1}$ centre trawl | | 3.72 |
| Wt of eastern king prawns, $ha^{-1}$ starboard trawl | Trawl configuration | 11.05** |
| Wt of eastern king prawns $ha^{-1}$ total system | Trawl configuration | 7.97* |
| No. of eastern king prawns $ha^{-1}$ total system | Trawl configuration | 10.44** |
| Mean CL of eastern king prawns total system | | |
| Wt of by-product $ha^{-1}$ port trawl | Trawl configuration | 6.96* |
| Wt of by-product $ha^{-1}$ centre trawl | | 2.41 |
| Wt of by-p product $ha^{-1}$ starboard trawl | Trawl configuration | 10.86** |
| Wt of by-product $ha^{-1}$ total system | | 3.30 |
| No. of by-product $ha^{-1}$ total system | | 3.26 |
| Wt of bycatch $ha^{-1}$ port trawl | Trawl configuration | 10.11** |
| Wt of bycatch $ha^{-1}$ centre trawl | Trawl configuration | 5.70 |
| Wt of bycatch $ha^{-1}$ starboard trawl | Trawl configuration | 23.51*** |
| Wt of bycatch $ha^{-1}$ total system | Trawl configuration | 13.10** |
| No. of ret. cuttlefish, *Sepia* spp. $ha^{-1}$ total system | | 1.95 |
| Wt of ret. cuttlefish $ha^{-1}$ total system | | 1.88 |
| No. of ret. smooth bugs, *Ibacus chacei* $ha^{-1}$ total system | | 0.69 |
| Wt of ret. smooth bugs $ha^{-1}$ total system | | 0.47 |
| No. of ret. octopus, *Octopus* sp $ha^{-1}$ total system | | 2.96 |
| Wt of ret. octopus $ha^{-1}$ total system | | 4.17 |
| No. of ret. squid, *Lolligo* sp $ha^{-1}$ total system | | 1.53 |
| Wt of ret. squid $ha^{-1}$ total system | | 1.66 |
| No. of ret. red mullet, *Upeneichthys lineatus* $ha^{-1}$ total system | Trawl configuration | 6.84* |

| | | |
|---|---|---|
| Wt of ret. red mullet ha$^{-1}$ total system | Trawl configuration | 9.46** |
| No. of ret. EBSF, *Platycephalus caeruleopunctatus* ha$^{-1}$ total system | | 0.79 |
| Wt of ret. EBSF ha$^{-1}$ total system | | 1.21 |
| No. of ret. blue swimmer crabs, *Portunus pelagicus* ha$^{-1}$ total system | | 0.91 |
| Wt of ret. blue swimmer crabs ha$^{-1}$ total system | | 0.86 |
| No. of ret. stout whiting, *Sillago robusta* ha$^{-1}$ total system | | 0.06 |
| Wt of ret. stout whiting ha$^{-1}$ total system | | 0.13 |
| No. of ret. red spot whiting, *Sillago flindersi* ha$^{-1}$ total system | | 0.33 |
| Wt of ret. red spot whiting ha$^{-1}$ total system | | 0.52 |
| No. of disc. cuttlefish ha$^{-1}$ total system | | 0.22 |
| Wt. of disc. cuttlefish ha$^{-1}$ total system | | 0.43 |
| No. of disc. smooth bugs, *Ibacus chacei* ha$^{-1}$ total system | | 2.76 |
| Wt of disc. smooth bugs ha$^{-1}$ total system | | 2.45 |
| No. of disc. EBSF ha$^{-1}$ total system | | 1.08 |
| Wt of disc. EBSF ha$^{-1}$ total system | | 1.33 |
| No. of disc. gurnard, *Lepidotrigla argus* ha$^{-1}$ total system | | 1.07 |
| Wt of disc. gurnard ha$^{-1}$ total system | | 0.38 |
| No. of disc. long-spine flathead, *Platycephalus longispinis* ha$^{-1}$ total system | Trawl configuration | 6.31* |
| Wt. of disc. long-spine flathead ha$^{-1}$ total system | Trawl configuration | 11.70** |
| No. of disc. founder, *Pseudorhombus* spp.ha$^{-1}$ total system | | 1.31 |
| Wt of disc. flounder ha$^{-1}$ total system | | 0.16 |
| No. of disc. spikey flathead, *Ratabulus diversidens* ha$^{-1}$ total system | | 0.95 |
| Wt of disc. spikey flathead ha$^{-1}$ total system | | 2.62 |

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

**Table 2.** Summaries of selected performance indicators for configurations comprising either three Florida flyers (15.20-m headlines) or Seibenhausers (15.31-m) or two W trawls (18.38 m) either side of a Florida flyer (9.14 m). Where appropriate, the predicted means (± SE) from linear mixed models are provided and were calculated with centred significant continuous covariates. Spread ratio was calculated as total wing-end spread ÷ total headline length. Average drag was calculated at a mean speed of 1.24 m $s^{-1}$. Dissimilar superscript letters indicate significant differences detected in false-discovery-rate pairwise comparisons (*P* < 0.05).

| | | Configuration | |
|---|---|---|---|
| Variable | Florida-flyer | Seibenhauser | W-trawl |
| Total spread ratio | $0.66 \pm 0.005^{B}$ | $0.63 \pm 0.005^{C}$ | $0.73 \pm 0.005^{A}$ |
| Area trawled (ha) | $30.75 \pm 0.86^{A,B}$ | $29.82 \pm 0.84^{B}$ | $33.21 \pm 0.88^{A}$ |
| Otter board angle of attack (°) | 33.15 ± 0.14 | 32.17 ± 0.07 | 38.16 ± 0.12 |
| Drag (kgf) | $1943.88 \pm 59.39^{A}$ | $1849.82 \pm 59.51^{A}$ | $1953.16 \pm 61.54^{A}$ |
| Fuel | | | |
| L $h^{-1}$ | $32.82 \pm 0.82^{A}$ | $32.40 \pm 0.82^{A}$ | $32.88 \pm 0.90^{A}$ |
| L $ha^{-1}$ | $5.53 \pm 0.45^{A,B}$ | $5.57 \pm 0.46^{B}$ | $5.33 \pm 0.45^{A}$ |

**Captions to Figs**

Fig. 1. Plan of the (a) 15.20-m Florida-flyer, and (b) 15.20-m Seibenhauser trawls.

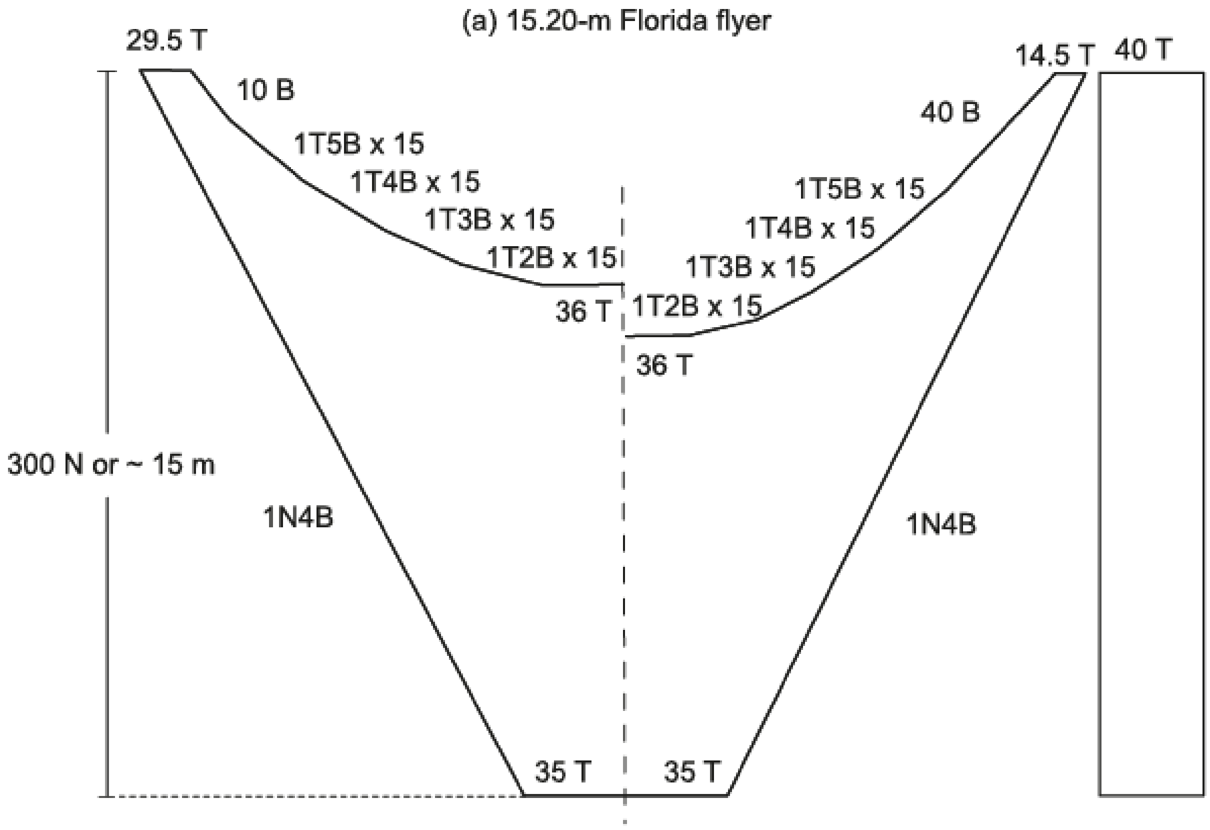
Fig. 2. Plan of the (a) 18.38-m W, and (b) 9.14-m Florida flyer trawls.

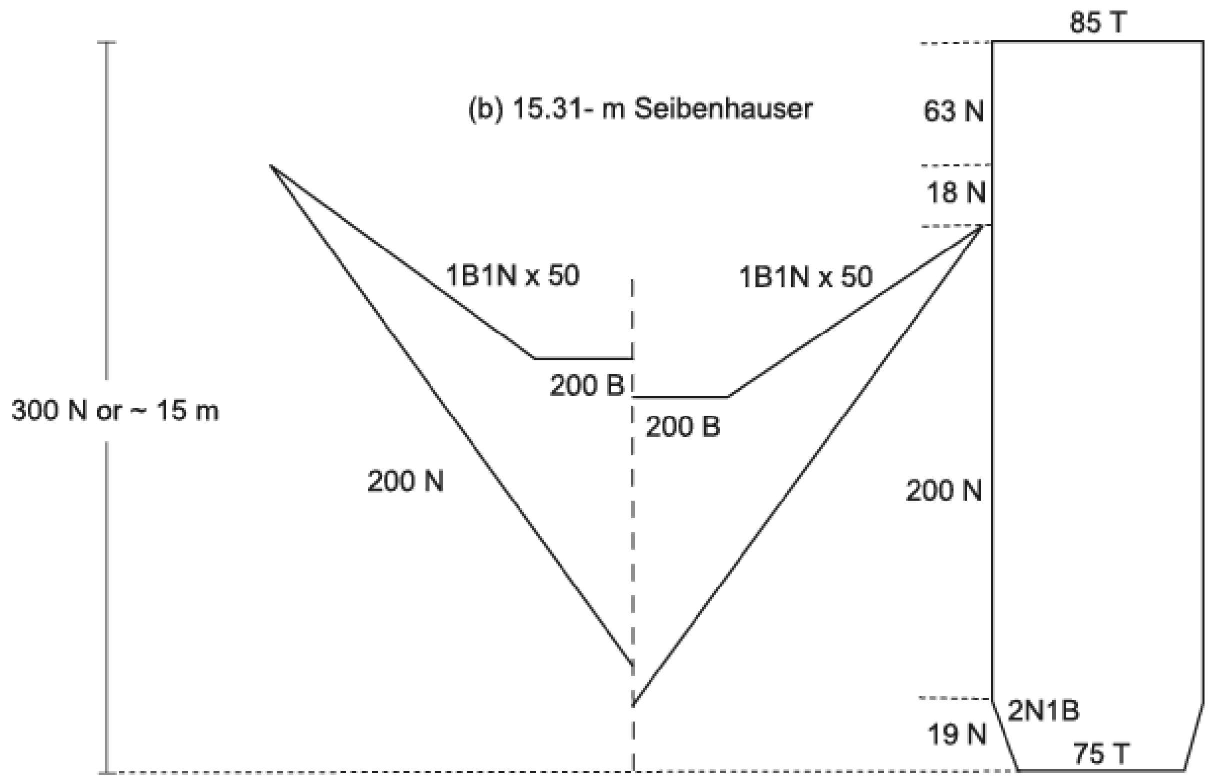
Fig. 3. Top view of the vessel and triple-rigged (a) the two outside W-, and centre Florida-flyer trawls and (b) Florida-flyer and Seibenhauser trawls. Sweep lengths given in m.

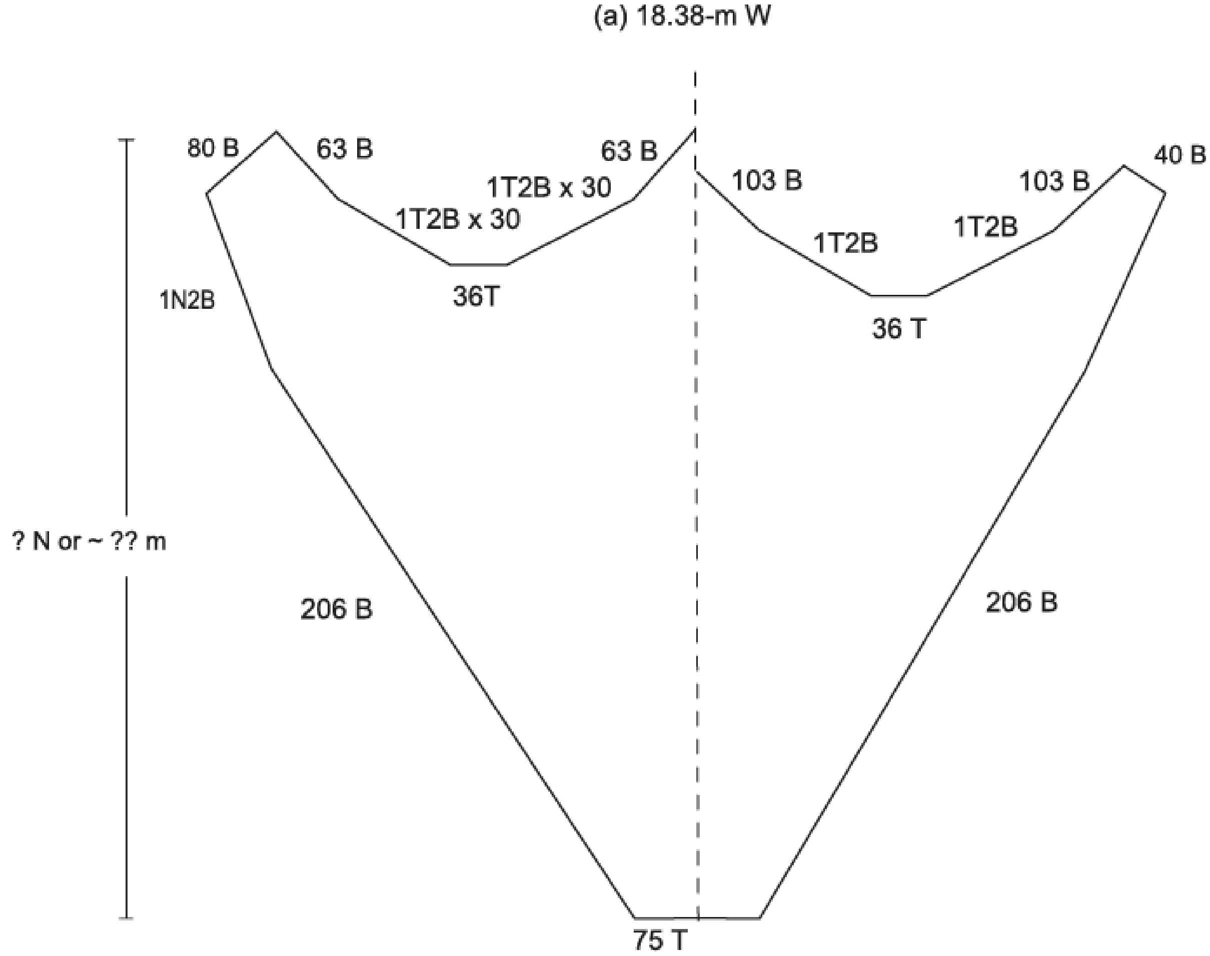
Fig. 4. Differences in predicted mean ± SE spread ratios of the side- and centre-trawls and total system for each trawl configuration.

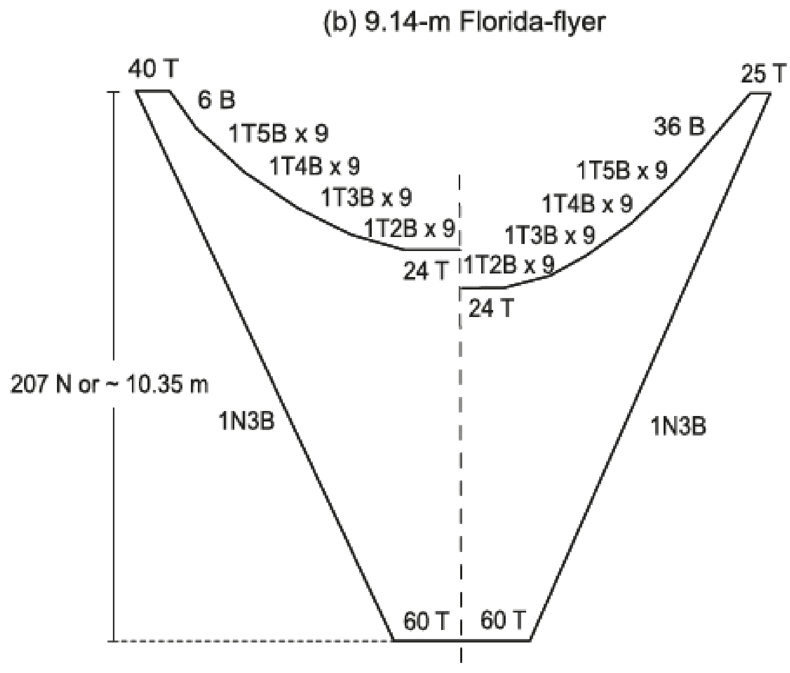
Fig. 5. Differences in predicted mean weights $ha^{-1}$ trawled of (a) eastern king prawns, *Penaeus plebejus* (b) by-product and (c) bycatch between the side and centre trawls for each configuration.

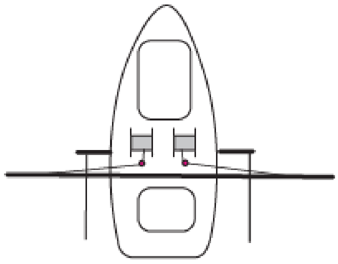
Fig. 6. Differences in predicted mean weights $ha^{-1}$ trawled of (a) retained red mullet, *Upeneichthys lineatus*, and (b) discarded long-spine flathead, *Platycephalus longispinis* pooled across the three trawls (i.e. total system) within each configuration.

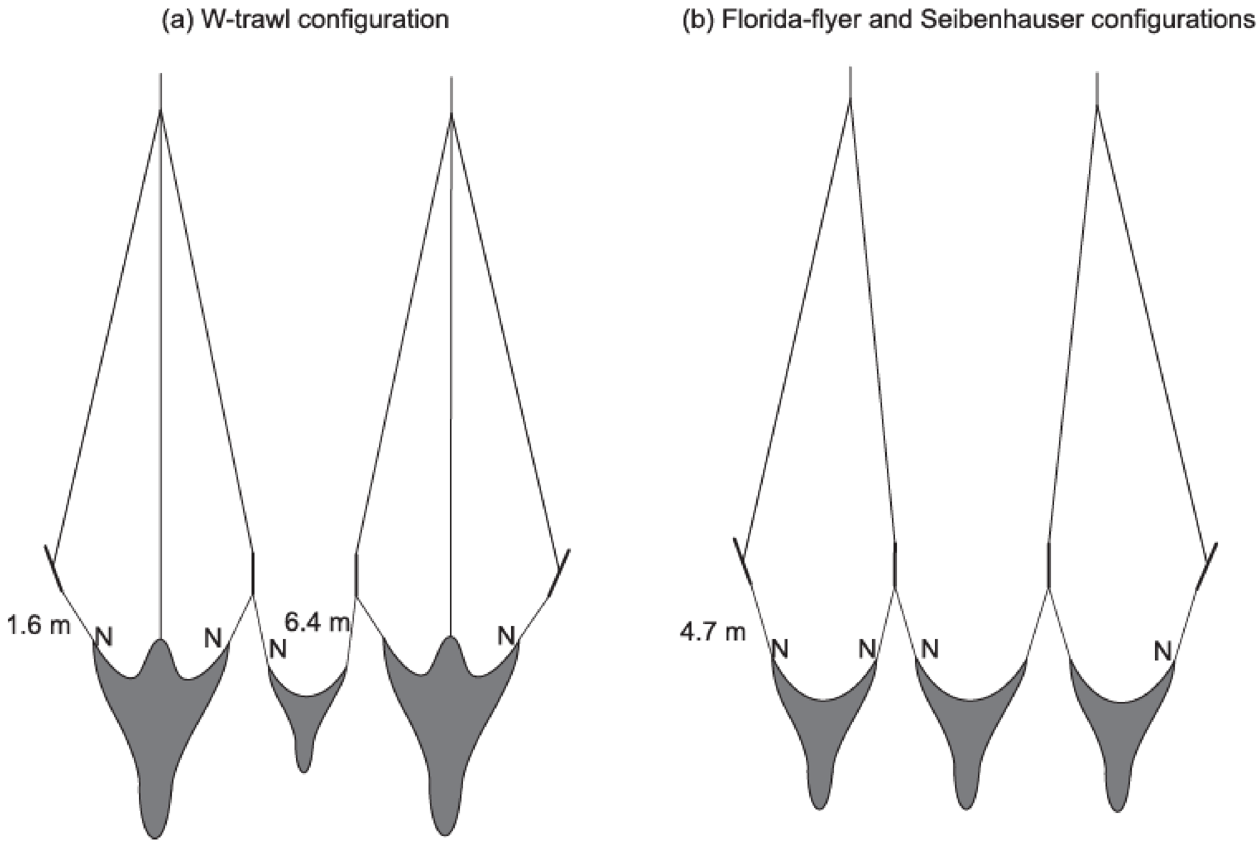

(a) 15.20-m Florida flyer
29.5 T
10 B
1T5B x 15
1T4B x 15
1T3B x 15
1T2B x 15
36 T
14.5 T
40 T
40 B
1T5B x 15
1T4B x 15
1T3B x 15
1T2B x 15
36 T
300 N or ~ 15 m
1N4B
1N4B
35 T
35 T


85 T
(b) 15.31- m Seibenhauser
63 N
18 N
1B1N x 50
1B1N x 50
200 B
200 B
300 N or ~ 15 m
200 N
200 N
2N1B
19 N
75 T

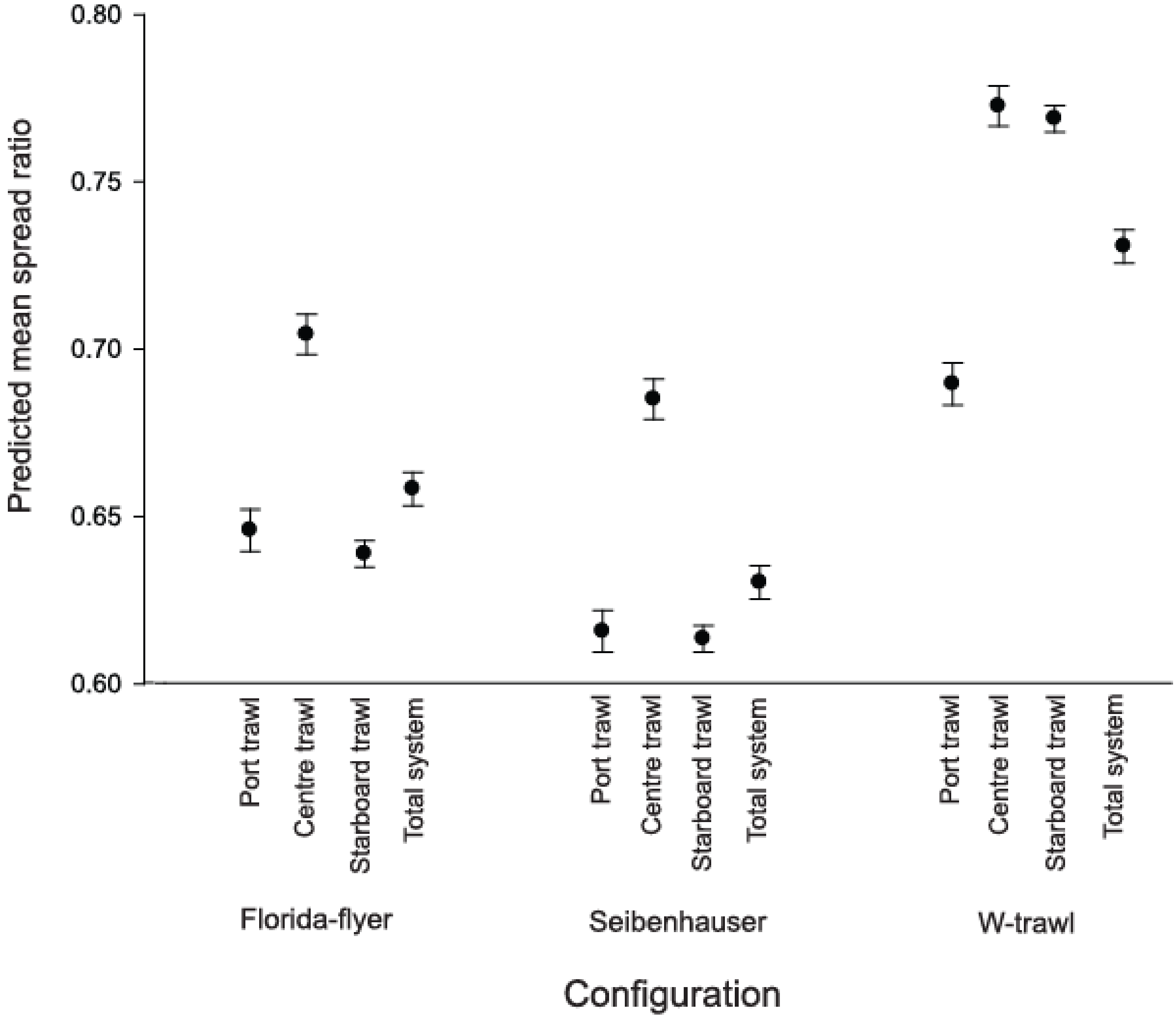

(a) 18.38-m W
80 B
63 B
63 B
1T2B x 30
1T2B x 30
36T
103 B
103 B
40 B
1T2B
1T2B
36 T
1N2B
? N or ~ ?? m
206 B
206 B
75 T

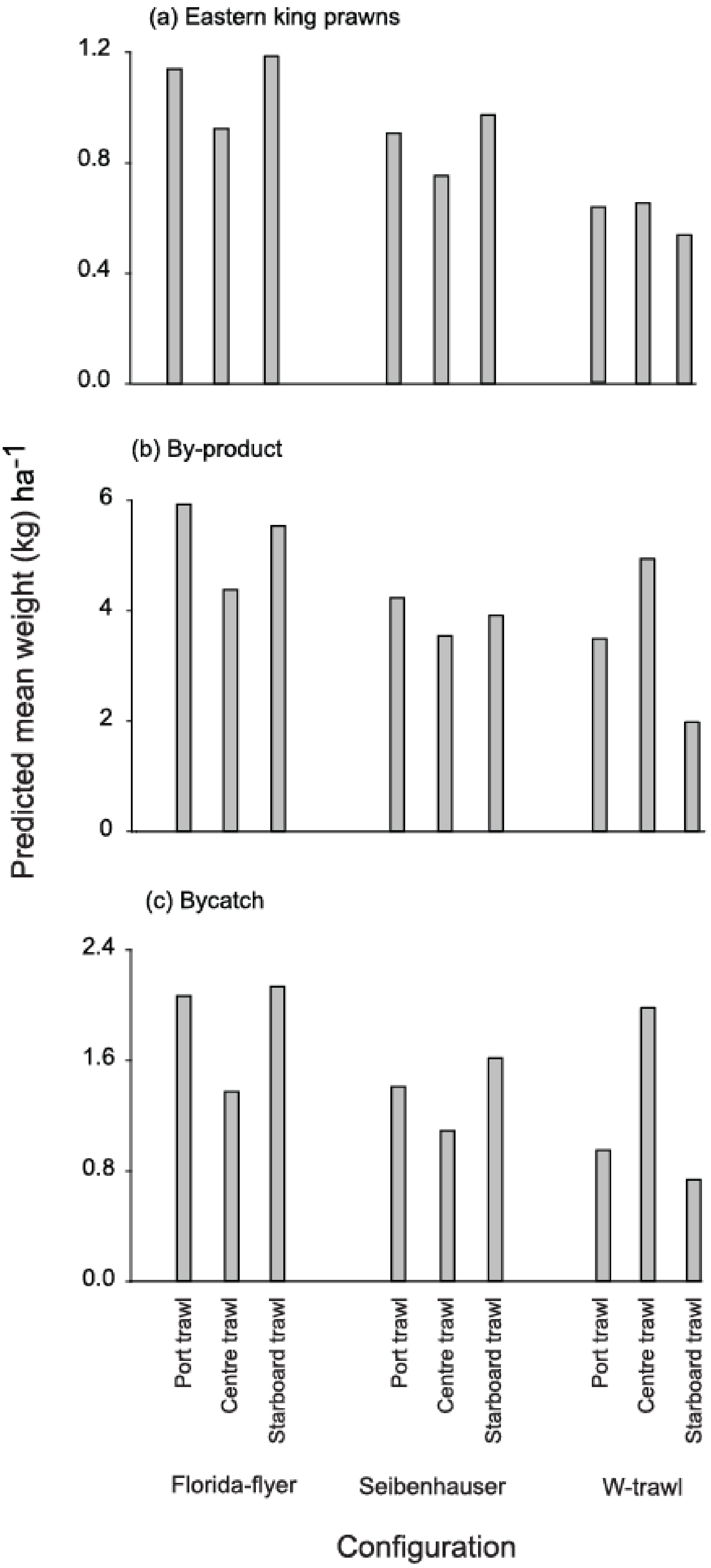

(b) 9.14-m Florida-flyer
40 T
6 B
1T5B x 9
1T4B x 9
1T3B x 9
1T2B x 9
24 T
25 T
36 B
1T5B x 9
1T4B x 9
1T3B x 9
1T2B x 9
24 T
207 N or ~ 10.35 m
1N3B
1N3B
60 T
60 T



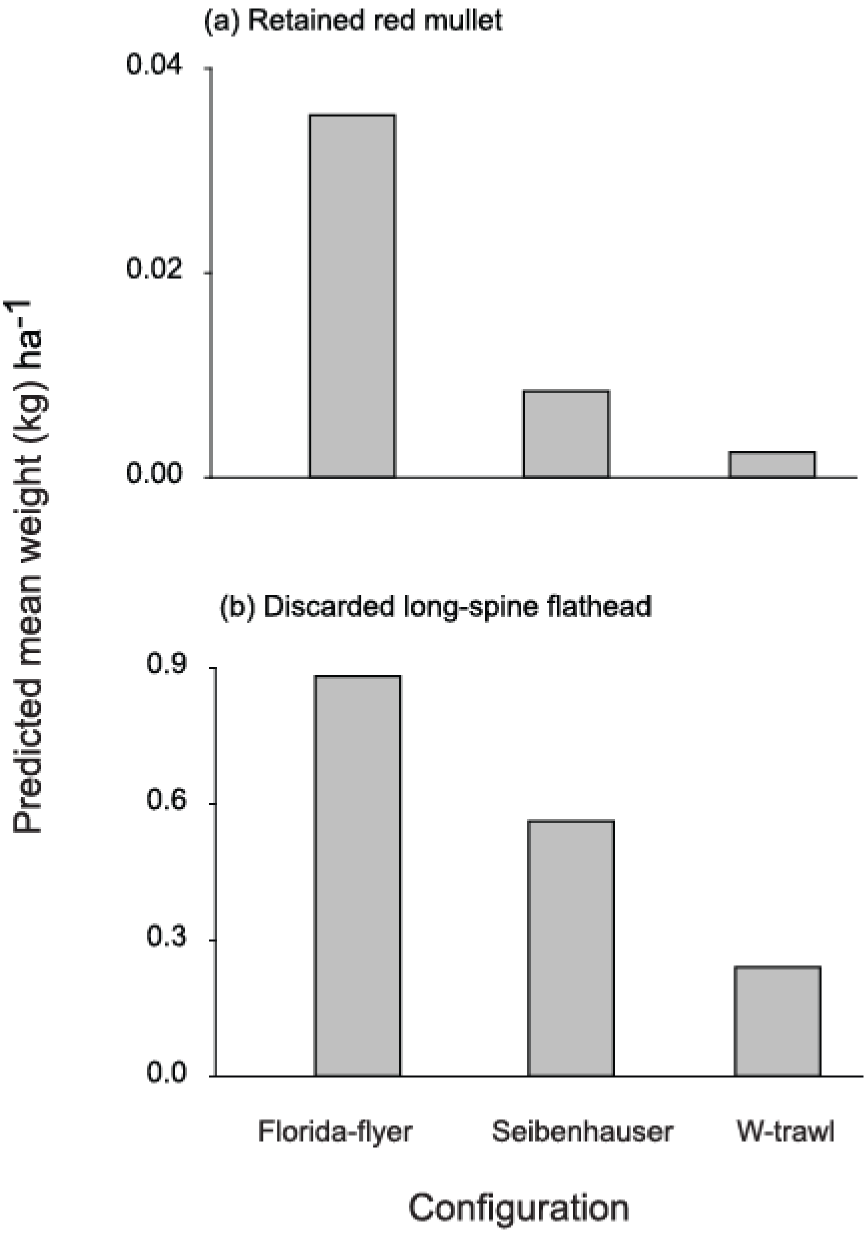


(a) W-trawl configuration
(b) Florida-flyer and Seibenhauser configurations
1.6 m
N
N
N
6.4 m
N
4.7 m
N
N
N
N


0.80
0.75
0.70
0.65
0.60
Predicted mean spread ratio
Port trawl
Centre trawl
Starboard trawl
Total system
Port trawl
Centre trawl
Starboard trawl
Total system
Port trawl
Centre trawl
Starboard trawl
Total system
Florida-flyer
Seibenhauser
W-trawl
Configuration



(a) Eastern king prawns
1.2
0.8
0.4
0.0
(b) By-product
6
4
2
0
(c) Bycatch
2.4
1.6
0.8
0.0
Predicted mean weight (kg) ha-1
Port trawl
Centre trawl
Starboard trawl
Port trawl
Centre trawl
Starboard trawl
Port trawl
Centre trawl
Starboard trawl
Florida-flyer
Seibenhauser
W-trawl
Configuration


(a) Retained red mullet
0.04
0.02
0.00
Predicted mean weight (kg) ha-1
(b) Discarded long-spine flathead
0.9
0.6
0.3
0.0
Florida-flyer
Seibenhauser
W-trawl
Configuration

**Appendix 18**. Balash, C., Sterling, D., Broadhurst, M., Dubois, A. and Behrel, M. 2015. Hydrodynamic evaluation of a simple sail used in an innovative prawn-trawl otter board. Proceedings of the 34th international conference on ocean, offshore and Arctic engineering (May 31 to June 5, 2015), St John's, Newfoundland, Canada.

Proceedings of the 34th International Conference on Ocean, Offshore and Arctic Engineering
OMAE15
May 31 – June 5, 2015, St. John's, NL, Canada

# OMAE2015-41335

# HYDRODYNAMIC EVALUATION OF A GENERIC SAIL USED IN AN INNOVATIVE PRAWN-TRAWL OTTER BOARD

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## ABSTRACT

In prawn-trawling operations, otter boards provide the horizontal force required to maintain net openings, and are typically low aspect ratio (~0.5) flat plates operating on the seabed at high angles of attack (AOA; 35–40°). Such characteristics cause otter boards to account for up to 30% of the total trawling resistance, including that from the vessel. A recent innovation is the batwing otter board, which is designed to spread trawls with substantially less towing resistance and benthic impacts. A key design feature is the use of a sail, instead of a flat plate, as the hydrodynamic foil. The superior drag and benthic performance of the batwing is achieved by (i) successful operation at an AOA of ~20° and (ii) having the heavy sea-floor contact shoe in line with the tow direction. This study investigated the hydrodynamic characteristics of a generic sail by varying its twist and camber, to identify optimal settings for maximum spreading efficiency and stability. Loads in six degrees of freedom were measured at AOAs between 0 and 40° in a flume tank at a constant flow velocity, and with five combinations of twist and camber. The results showed that for the studied sail, the design AOA (20°) provides a suitable compromise between greater efficiency (occurring at lower AOAs) and greater effectiveness (occurring at higher AOAs). At optimum settings (20°, medium camber and twist), a lift-to-drag ratio >3 was achieved, which is ~3 times more than that of contemporary prawn-trawling otter boards. Such a result implies relative drag reductions of 10–20% for trawling systems, depending on the rig configuration.

## INTRODUCTION

An otter board is a hydrodynamic wing, traditionally comprising a flat plate rigged at an angle of attack (AOA) to produce lift or shear and the desired horizontal force to a trawl system. The classic Australian prawn-trawl otter boards have a geometric aspect ratio of ~0.5 and are operated at 35–40° to ensure stability during all phases of the fishing operation.


**FIGURE 1. BATWING OTTER BOARD RIGGING**

Furthermore, because such otter boards are heavy, the friction and ploughing of their contact on the sea floor (typically via a steel base plate) generates additional resistance force and can damage seabed structures and benthic organisms. These characteristics result in poor spreading efficiency with a lift-to-drag (L/D) ratio of ~1 (SFIA & DIFTA, 1995) which means otter boards can account for up to 30% of the total trawling resistance, including that from the vessel (Balash & Sterling, 2012).

To address the above issues, Sterling (2008) proposed a 'batwing' otter board (Figure 1). The device comprises a sled (towed parallel to the direction of tow), from which a flexible sail is hinged posteriorly and attached by chain at the leading edge. The location of the lower-aft point of the sail (tack) can be adjusted, such that a vertical displacement affects the twist of the sail, whereas a longitudinal shift changes the camber. The AOA is set by the extension of the boom, which changes the position of the centre-of-pressure (COP) relative to the connection points for the towing wire and the trawl. The resultant of the in-pulling force applied to the attachment pole must, at equilibrium, be lined up with the resultant of the hydrodynamic forces (applying at the COP). The length of the front chain (linking the fronts of the heavy contact shoe and boom) is adjusted to align the shoe with the towing direction. This latter characteristic implies that compared to the same sized conventional otter board, the batwing has up to 90% less sea floor contact span (Figure 2).

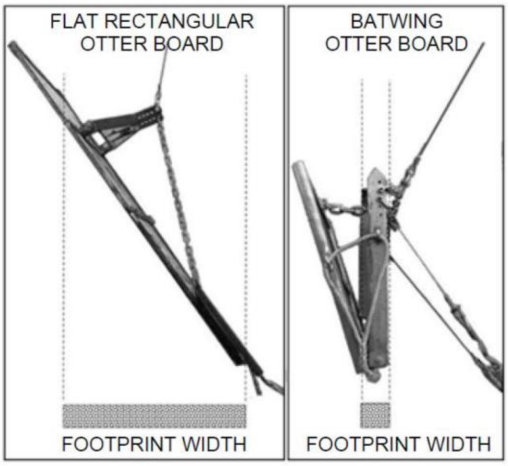


**FIGURE 2. SEA FLOOR CONTACT SPAN FOR TRADITIONAL (LEFT) AND BATWING (RIGHT) OTTER BOARDS**

Another key feature of the batwing otter board is that the towing wire (bridle) and the trawl wing are connected at the same longitudinal location (Figure 2). During deployment, conventional otter boards orientate at much lower AOAs than when on the bottom. To ensure a positive AOA, and therefore deployment stability, conventional otter boards are set at greater than ideal angles to spread the trawls. By comparison, the batwing otter board operates like a kite, which means that its AOA remains unaffected by the operational phase.

In a recent study, McHugh et al. (2015) demonstrated that the batwing had up to ~86% less sea floor contact and 18% less overall drag than three conventional otter-board designs. Although not formally validated, such a reduction in contact might be expected to translate to relatively less habitat disturbance.

As part of attempts to further optimise the efficiency of the batwing otter board, our aims here were to evaluate a generic sail in a flume tank with respect to the effects of twist and camber. Specifically, we sought to identify those settings and an operational AOA that produce the optimum L/D ratio, spreading force and stability combination.

## METHODS

The experiments were completed at the Australian Maritime College flume tank in Beauty Point, Tasmania. This facility consists of a recirculating flow tank of fresh water, measuring 17.2 m long, 5.0 m wide, and 2.5 m deep.

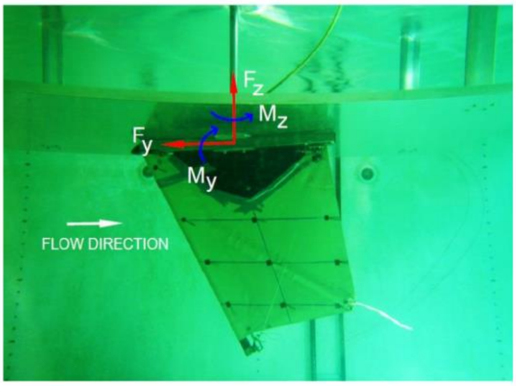


**FIGURE 3. MODEL SAIL TESTED IN THE FLUME TANK (THE MODEL WAS INVERTED TO FACILITATE ALTERING ANGLE OF ATTACK AND LOAD MEASUREMENTS FOR ALL SIX DEGREES OF FREEDOM). $F_X$ AXIS IS PERPENDICULAR TO THE FLOW, AND DIRECTED AWAY FROM THE OBSERVER**

A single sail at 0.78 scale (termed # 3 to represent the relative trawl gear size) and associated mast and boom were used in the experiment (Figure 3 and Table 1). This sail had a mast rake of 30° and contained a single batten, which supported a large head (Figure 1). The sail was attached through a large flat plate to a vertical rotating sting via a six-channel load cell. The sting allowed the sail to be rotated to the required AOA, with the flat plate simulating the sea floor boundary.

Five sail settings ('cases') were evaluated (Table 2). These cases systematically varied both the camber and the twist of the sail through three positions, specified as low (including the 'base' case), medium and high. To vary the sail's camber, an aft sliding track was adjusted to alter the chord length at the foot of the sail by 10-mm (~1% of the foot length) increments, which produced medium and high camber relative to the low setting. There were also three reinforced holes (25 mm apart) on the aft end of the sail foot. These holes aligned with a connecting pin on the slider track and facilitated adjusting the leech to produce sail twist.

**TABLE 1. SAIL, MAST AND BOOM DIMENSIONS**

| Characteristic | | |
|---|---|---|
| **Sail** | Foot length | 930 mm |
| | Sail height | 900 mm |
| | Battens | 1 |
| | Head length | 550 mm |
| **Mast** | Diameter | 50 mm |
| | Length | 1025 mm |
| | Rake angle | 30° |
| **Boom** | | 50 x 50 SHS |
| **Aspect ratio** | | 1.23 |
| **Plan-form surface area** | | 0.65 $mm^2$ |

**TABLE 2. TWIST-AND-CAMBER COBMINATIONS**

| | | |
|---|---|---|
| **Case 1 -** low twist, low camber | | **Case 3 -** low twist, high camber |
| | **Case 5 -** medium twist, medium camber | |
| **Case 7 -** high twist, low camber | | **Case 9 -** high twist, high camber |

Each of the five cases was tested over various AOAs from 0 to 40° at a flow of 0.5 m $s^{-1}$. The load cell had a maximum capacity of 250 pound force. Measurements were recorded at a frequency of 5 Hz over 10 s. Data for each AOA were collected twice, which resulted in 102 data points for each force/torque variable in each combination of AOA and twist/camber setting.

The load-cell manufacturer-supplied correction matrix was used to remove the confounding effects of cross-talk between the channels of the load cell. Additionally data were collected from the test rig for a rigid flat plate across AOAs from 90 to -90°. These data were used to update the cross-talk correction matrix so that the hydrodynamic results for the flat plate were correctly symmetrical for positive and negative AOA ranges.

Lift and drag were estimated with Eqs. 1 and 2 respectively:

$$Lift = F_x \cos(AOA) - F_y \sin(AOA) \quad (1)$$

$$Drag = -F_x \sin(AOA) - F_y \cos(AOA) \quad (2)$$

The longitudinal centre-of-pressure ($COP_y$) at a given operational AOA was estimated with Eq. 3:

$$COPy = \frac{\left(Sail_L - Cell_D + \left(\frac{M_z}{F_x}\right)\right)}{Sail_L} \quad (3)$$

where $Sail_L$ is length of the sail, $Cell_D$ is distance from trailing edge of the boom to load cell centre, and $M$ and $F$ are moment and force respectively as per Figure 3.

The flume tank generally provides steady and repeatable relative measurements. To demonstrate the general level of variance in the data, 95% confidence intervals for lift, drag and L/D at 20° AOA were estimated from the variance observed in the replicated measurements of body-fixed forces and using the rules for variance propagation given in Eq. (4) to calculate the associated variance in the flow-fixed forces and their ratio (L/D):

$$y = f\,(x_1, x_2)$$

$$\sigma_y^2 = \left(\frac{\delta f}{\delta x_1}\right)^2 \sigma_{x_1}^2 + \left(\frac{\delta f}{\delta x_2}\right)^2 \sigma_{x_2}^2 + 2\frac{\delta f}{\delta x_1}\frac{\delta f}{\delta x_2}\sigma_{x1}\sigma_{x2} \quad (4)$$

No covariance was considered because $F_x$ and $F_y$ were assumed to be independent of each other.

## RESULTS AND DISCUSSION

The lift, drag and L/D ratio results for the five tested combinations of sail twist and camber are summarised in Figure 4 and Table 3. The lift and drag produced by the cases were similar, but there were subtle differences owing to the effects of twist and camber.

The lift-curves for the sail had a major peak at between 21 and 24°, and a secondary strengthening of lift at higher AOA. The drag responses were positively associated with AOA. Across all cases, the maximum L/D ranged between 4.0 and 4.7 at 10 to 16° AOA. Considering the greatest efficiency at low AOA, but greatest effectiveness (lift) at higher AOAs, the design AOA of 20° seems to be a reasonable compromise.

The stall angle can be defined where lift stops increasing with increasing AOA due to flow separation (which most likely starts occurring at less than the stall angle). Overall, the most lift (42.0 N) produced by the sail occurred for case 9 (high twist, high camber) at the stall angle of 24°. Compared to the base case (case 1 - low twist, low camber), a high maximum lift at a slightly higher AOA also occurred for case 3 (low twist, high camber). Therefore, high chamber produced increased maximum lift, presumably due to the delay of flow separation and continued growth of lift until stall occurred at a higher angle.

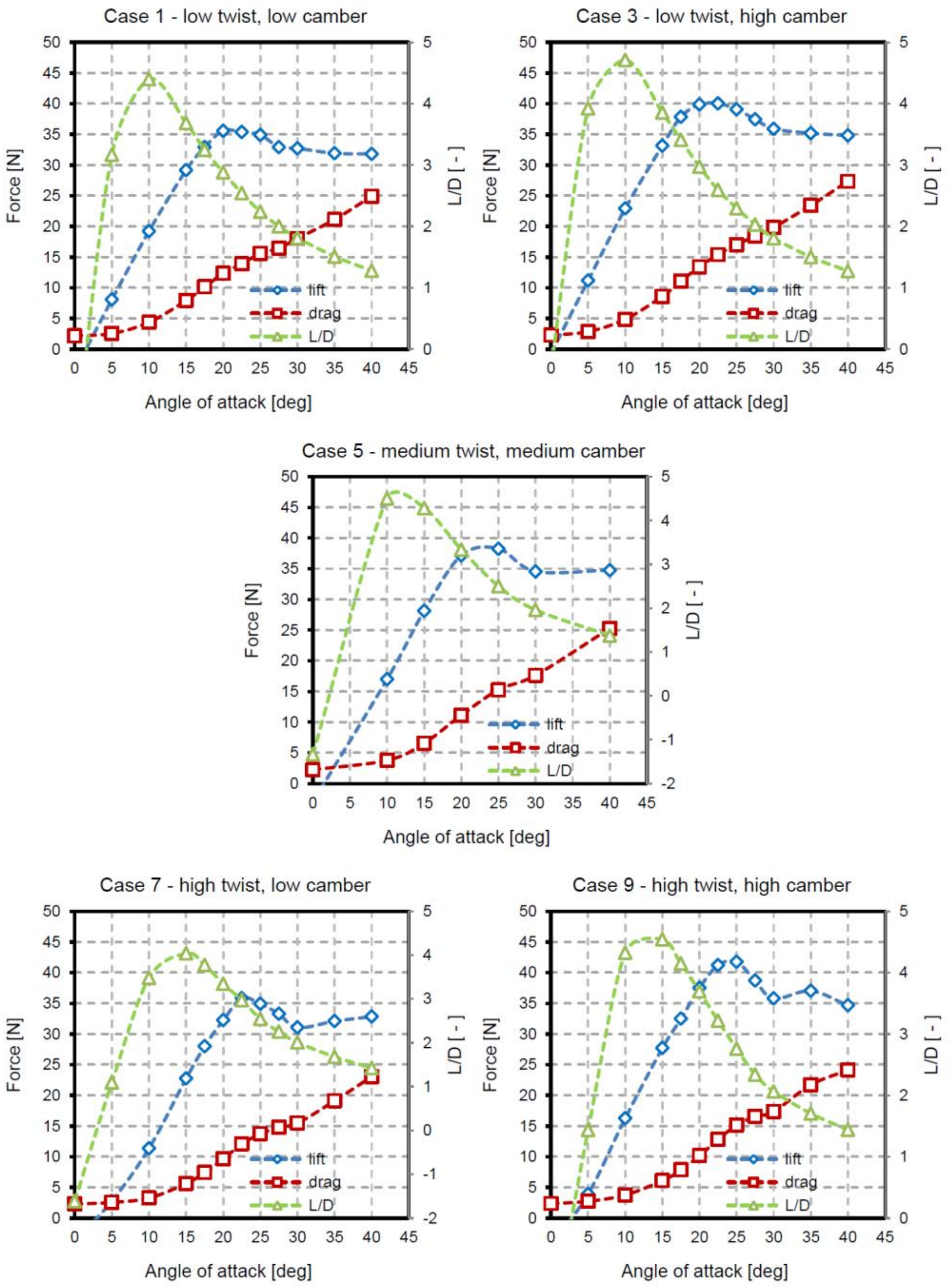


**FIGURE 4. LIFT, DRAG AND LIFT-TO-DRAG (L/D) RATIO**

**TABLE 3 MAJOR HYDRODYNAMIC CHARACTERISTICS OF THE SAIL, WITH 95% CONFIDENCE INTERVALS FOR PARAMETERS AT 20° ANGLE OF ATTACK**

| Case | 1 | 3 | 5 | 7 | 9 |
|---|---|---|---|---|---|
| Lift at stall [N] | 35.6 | 40.0 | 38.3 | 36.0 | 42.0 |
| Stall AOA [°] | 21.0 | 22.0 | 23.0 | 23.0 | 24.0 |
| Drag at stall [N] | 12.4 | 15.0 | 15.0 | 12.1 | 15.0 |
| Maximum L/D | 4.4 | 4.7 | 4.6 | 4.0 | 4.6 |
| Maximum L/D AOA [°] | 11.0 | 10.0 | 12.0 | 16.0 | 13.0 |
| Lift at 20° AOA [N] | 35.6 ± 0.2 | 40.0 ± 0.2 | 37.2 ± 0.1 | 32.2 ± 0.1 | 37.5 ± 0.1 |
| Drag at 20° AOA [N] | 12.4 ± 0.1 | 13.4 ± 0.1 | 11.1 ± 0.0 | 9.6 ± 0.1 | 10.2 ± 0.0 |
| L/D at 20° AOA | 2.9 ± 0.0 | 3.0 ± 0. | 3.3 ± 0.0 | 3.3 ± 0.0 | 3.7 ± 0.0 |
| COP movement aft for 20° to 5° AOA change [% of chord] | -9% | -1% | -3% | -13% | 32% |

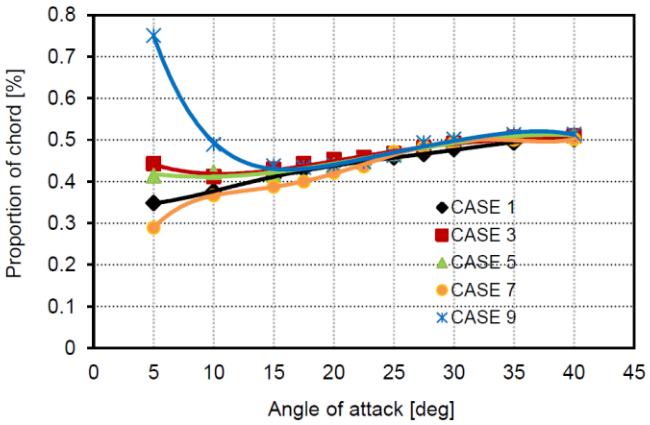


**FIGURE 5. CHORD WISE LOCATION OF LONGITUDINAL CENTRE OF PRESSURE VS. ANGLE OF ATTACK**

In contrast, case 7 (high twist, low camber) indicated twist produced no substantive increase in maximum lift, but returned the lowest drag and noticeably raised the stall angle. The action of twist was probably an appropriate reduction in local AOA for the top half of the sail—considering the likely up-wash in that area due to the effect of mast rake (Hurt, 1965). Presumably this effect considerably reduced drag in the upper part of the sail. Specifically, strong twisting in sails reduces the prospect of premature stall at the tip and orientates the surface to produce efficient lift at higher AOAs. The concomitant drag reductions are achieved by (i) preventing strong vortices occurring around the sail tip and (ii) reducing the effects of finite aspect ratio on induced drag by improving the span-wise lift distribution (ideally elliptical; Abbott and Von Doenhoff, 1959).

The highest L/D ratio of 4.7 occurred for case 3 at a 10° AOA, while case 7 produced the lowest maximum L/D at the highest AOA of 16°. At the design AOA of 20°, the highest L/D ratio was 3.7 from case 9; however, case 7 also showed a strong improvement relative to the base case and so did case 5 (medium twist, medium camber). Case 3 produced very limited improvement in L/D at 20°, suggesting that efficiency is positively associated with twist at 20° and with camber at lower AOAs.

These results indicate that the tested sail achieves a L/D considerably higher than 3 for the design AOA of 20° across various settings (albeit all had twist). These cases produce even higher L/D at smaller AOAs (about 4.6 at 13°), but at this point the otter board would produce a very low spreading force (about half that at 20°). At 20°, the most spreading force (lift) was produced by case 3, but with low efficiency because of no twist in that setting. Case 9 had the next strongest lift at 20° combined with the highest L/D of all cases at that AOA. Case 7 had relatively high L/D but the lowest lift of all cases. Case 5, having both camber and twist (a medium version of case 9), produced relatively high values of both lift and L/D at 20°, but less than those achieved by case 9.

To illustrate the AOA stability of the sail-foil when performing its role in an otter board, Figure 5 presents the chord-wise location of COP over tested AOA and Table 3 presents the change in COP location for each case when the AOA is reduced from 20 to 5°. The low camber cases 1 and 7 had continuous forward movement of the COP as AOA was reduced. This is an ideal situation because the COP shift will tend to align the sail back to the desired AOA, whereas COP movement towards the trailing edge will enhance the sail's rotation towards low AOA and potentially cause the otter board to collapse. High camber (particularly case 9) caused unfavourable aft migration of the COP with reducing AOA from 20°. For the medium camber and medium twist settings, a low level of beneficial forward COP movement occurred. This result, combined with a strong spreading force and high efficiency at 20°, makes case 5 the recommended setting for the tested sail.

## CONCLUSIONS

This study evaluated the effects of twist and camber across a range of AOAs on the spreading function and stability of one sail. We established that the design AOA (20°) provides a suitable compromise between greater efficiency (occurring at lower AOAs) and greater effectiveness (occurring at higher AOAs). We also demonstrated that a combination of camber and twist produced relatively strong values of both lift and efficiency at 20°, but high camber has to be avoided to ensure AOA stability during operation. At optimum settings (an AOA of 20°, medium camber and twist), a L/D of 3.3 was achieved, which is ~3 times more than that of contemporary prawn-trawling otter boards. Such a result implies relative drag reductions of 10–20% for trawling systems, depending on the rig configuration. Further research would benefit from evaluating other sail designs and sizes, including multi-foil devices.

## ACKNOWLEDGMENTS

The study was funded by the Australian Government Fisheries Research and Development Corporation (Project no. 2011/010), the Australian Maritime College and Sterling Trawl Gear Services.

## NOMENCLATURE

*AOA* – Angle of attack
$Cell_D$ – Distance from trailing edge of the boom to load cell centre
*COP* – Centre of pressure
*F* – Force
*L/D* – Lift-to-drag ratio
*M* – Moment
$Sail_L$ – Length of the sail

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**Appendix 19.** Balash, C., Sterling, D., Lustica, M. and Broadhurst, M.K. 2015. Twist-and-camber effects on the performance of simple hydro-sails for efficiently spreading penaeid trawls. Ocean Engineering 109: 161–168.

Ocean Engineering 109 (2015) 161–168

Contents lists available at ScienceDirect

Ocean Engineering

journal homepage: www.elsevier.com/locate/oceaneng

# Twist-and-camber effects on the performance of simple hydro-sails for efficiently spreading penaeid trawls

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ARTICLE INFO

*Article history:*
Received 15 April 2015
Accepted 30 August 2015

*Keywords:*
Batwing
Drag reduction
Fuel efficiency
Lift-to-drag ratio
Otter board
Sail performance

ABSTRACT

Penaeid-trawling fuel efficiency can be enhanced by using otter boards with high lift-to-drag ratios (*L*/*D*), which generally occurs at low angles of attack (AOA). The batwing otter board is such a low AOA solution; incorporating a unique towing arrangement and a high aspect ratio, flexible, hydro-sail to spread trawls with minimal seabed contact. This study investigated the effects of twist and camber on the performance of two simple batwing sails in a flume tank. Six degree-of-freedom loads were measured for AOAs between 0° and 40° for five twist and camber combinations. The major findings were that: (1) changing the mast rake angle from 30° to 45° reduced *L*/*D* at the design AOA of 20° by 12%, considering each sail's optimum setting; (2) stall angle increased for the higher rake angle, despite the associated sail having the greater aspect ratio; (3) irrespective of rake angle, camber was positively associated with lift whereas twist decreased drag and substantially increased *L*/*D* at the design AOA; and (4) a *L*/*D* ratio of ~3 was achieved or exceeded at 20° AOA for both sails, which is ~3 times greater than for contemporary otter boards, implying a 20% drag reduction for otherwise equivalent penaeid-trawling systems.


## 1. Introduction

More than 100 species of penaeids (known as shrimp or prawns, depending on the species and country) are targeted throughout the world's tropical and temperate oceans, and mostly in developing countries (Gillett, 2008). Various active and passive fishing gears are used to target these species, although the vast majority of production comes from 'otter trawling', which, according to Gillett (2008), typically involves multiple trawls that are dragged along the seabed from vessels between 8 and 25 m in length.

The input of fuel to penaeid trawling is costly; typically absorbing 30–50% of the fishing revenue (Wakeford, 2010). One of the major operational contributors towards such costs are the hydro-vanes (so-called 'otter boards') required to spread the trawls. Otter boards traditionally are rigged at 35–40° angle of attack (AOA) to provide a desired force perpendicular to the tow direction (Klaka and Sterling, 1993). In addition to the hydrodynamic forces of lift and drag, penaeid-trawl otter boards also create frictional and ploughing drag (and in many cases, cause associated habitat impacts) because they contact the seabed. Such characteristics mean that otter boards can account for 30% of the total system drag force (Balash and Sterling, 2012).

Historically, virtually all penaeid-trawl fisheries have used simple flat-rectangular otter boards. In some fisheries, especially those in developed countries like Australia (where the energy intensity of the operation is high), such conventional otter boards have been challenged by designs incorporating camber and slots that facilitate smooth water flow and delay stall. In many cases, such features manifest as a small improvement in otter-board hydrodynamic efficiency or lift-to-drag ratio (*L*/*D*) defined as the resulting spread force divided by the corresponding drag force.

Nevertheless, irrespective of hydrodynamic design, the typical *L*/*D* of conventional penaeid-trawl otter boards at their operational AOA remains around 1.05 (Sfia and Difta, 1995). This documented hydrodynamic efficiency is regarded to be very poor, especially when compared to aerodynamic foils widely used in sailing craft (*L*/*D* ~4.5 https://en.wikipedia.org/wiki/Forces_on_sails) or aeroplanes (Cessna 150 *L*/*D* ~7, Boeing 747 *L*/*D* ~17 https://en.wikipedia.org/wiki/Lift-to-drag_ratio). Considering the above, any strategy to improve penaeid-trawl otter-board *L*/*D* by simply incorporating efficient foil shapes is flawed. Rather, efforts should focus on the more basal issue of lowering operating AOA – because this

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http://dx.doi.org/10.1016/j.oceaneng.2015.08.065

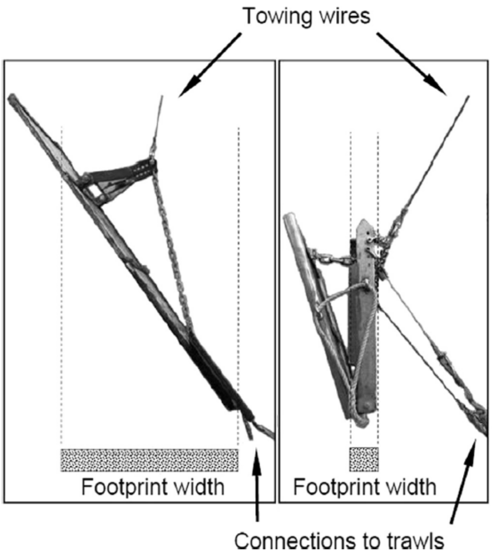

**Fig. 1.** Seabed contact for flat-rectangular (left) and batwing (right) otter boards.

mostly explains the incrementally superior *L*/*D* for sailing boats and aeroplanes (Sterling and Eayrs, 2010).

In an attempt to improve the hydrodynamic limitations of conventional otter boards, the 'batwing' design was proposed (Sterling, 2008), which comprises a high-aspect ratio foil that operates at a constant 20° AOA by utilising a unique rigging arrangement where the connections for the trawl net are moved to the same longitudinal position as the towing wire. A secondary design feature is the separation of the main seabed contact shoe from the hydrodynamic foil and its alignment with the tow direction (Fig. 1). Ultimately, the aim of the design is to (1) achieve a *L*/*D* ratio of 3 (thereby reducing drag), while (2) removing heavy scraping of the seabed and any associated habitat impacts (Sterling, 2010).

The first commercial prototype batwing board (CP1) was a rigid, multi-foil design, constructed by plastic welding various flat and curved polyethylene (PE) sheets together and bolting them onto a steel sled (Sterling, 2008). The foil design also included two vertical ventilation slots to reduce water-flow separation, and a cambered foil surface to make the chord-wise load distribution more uniform and improve efficiency (Sterling, 2008). Trials of a CP1 pair towed by a penaeid trawler off Queensland, Australia indicated that the design had half the drag of traditional otter boards, but the heavy weight of the PE foil and associated orientation issues during deployment (because the centre-of-gravity was too far outboard of the towing point) precluded commercial adoption (Sterling and Eayrs, 2010). An improvement termed CP2 had a robust flexible poly vinyl chloride (PVC) hydro-sail (henceforth referred to as 'sail' only), which was substantially lighter than the rigid PE foil and facilitated a more appropriate centre-of-gravity (Sterling, 2010). In a recent study in a New South Wales estuarine penaeid fishery, a small set of double-rigged CP2s (Fig. 2) maintained the same spreading force, but produced between 14% and 18% less overall drag than three conventional otter-board pairs (McHugh et al., 2015).

In addition to sea trials, a preliminary fume-tank investigation of the effect of twist and camber on hydrodynamic performance


**Fig. 2.** Second commercial prototype (CP2) batwing otter board being deployed in the field (McHugh et al., 2015).

occurred for a sail with a mast rake of 30° and containing one batten to support area at the sail head (Balash et al., 2015b). The tested subject was a 0.78 scale model of a CP2 sail (termed '#3' to indicate its relative full-scale size) being commercially trialled in Moreton Bay, Queensland. Based on this flume-tank work we concluded that the design AOA of 20° provided a suitable compromise between greater hydrodynamic efficiency (occurring at lower AOAs) and greater effectiveness, or spreading force (occurring at higher AOAs). Ultimately, at optimum settings (20° AOA, medium camber and medium twist), a L/D ratio of $>3$ was achieved, which is ~3 times more than that of contemporary penaeid-trawling otter boards (Balash et al., 2015b).

While the above results were promising, there is no information available on the effects of altering sail shape and whether simpler (and cheaper) configurations would have similar utility. Such relative information is important, given the dominance of small-scale penaeid-trawl fisheries in developing economies, where there is often a limited availability of resources for constructing efficient fishing-gear configurations.

Given the above, as part of a boarder objective to progress the batwing concept, our primary aim in this study was for optimisation purposes to quantify the effects of varying twist, camber and AOA on the spreading effectiveness, *L*/*D*, and stability of a full-scale sail, termed '#1". The #1 sail was a small, low cost design with a heavily-raked (45°) mast, and no batten; suited for implementation in a simplified batwing otter-board arrangement for small penaeid trawls. A secondary aim was to compare test data from the #1 sail with the previously-published data for the model #3 sail (30° rake, 1 batten arrangement designed for medium-sized trawls) (Balash et al., 2015b) to establish to what extent (if any) the simplicity of the #1 design compromised performance.

## 2. Materials and methods

Tests on the sails were conducted in the Australian Maritime College's flume tank at Beauty Point, Tasmania. This facility consists of a recirculating flow tank of fresh water with a test section measuring 17.2 m long, 5.0 m wide, and 2.5 m deep. Each of the #1 and model #3 sails (Fig. 3; Table 1) was installed on a carbon-fibre mast and stainless-steel boom with a flap on the high-pressure side to prevent flow between the boom and the sail's loose foot (Fig. 4). For all testing, the sails were inverted and attached through a ground plate (which simulated the presence of the seafloor boundary) to a vertical rotating arm ('sting') via a six-channel load cell. The sting allowed the sail arrangement to be rotated to a precise AOA.

**Fig. 3.** Side view of the #1 (left) and model #3 (right) sails.

**Table 1**
Sail, mast and boom details for #1 and #3 sails. Lengths in mm, areas in $m^2$; NA-not applicable.

| Characteristic | | #1 sail | #3 sail | Material |
|---|---|---|---|---|
| **Sail** | Scale | 1 | 0.78 | Polyvinyl chloride |
| | Foot length | 950 | 930 | |
| | Sail height | 1000 | 900 | |
| | Head length | 0 | 550 | |
| | Battens | 0 | 1 | Fibre glass |
| **Mast** | Rake | 45° | 30° | Carbon fibre |
| | Diameter | 50 | 50 | |
| | Length | 1420 | 1025 | |
| **Boom** | | 50 × 50 | 50 × 50 | Stainless steel |
| **Aspect ratio** ($\lambda$) | | 2 | 1.23 | NA |
| **Surface area** | | 0.515 | 0.654 | NA |

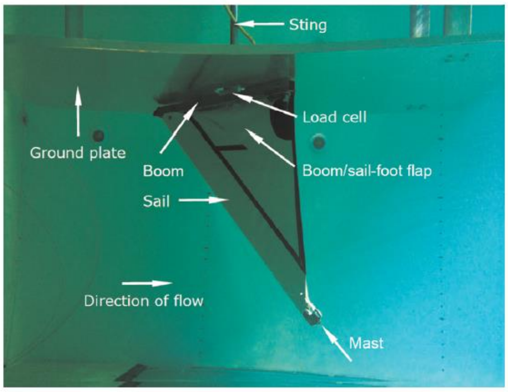


**Fig. 4.** Batwing #1 sail tested in the flume tank (the subject is inverted to enable alterations of angle of attack and load measurements for all six degrees-of-freedom).

Five settings were applied to each sail (Table 2). Case 1 was nominated as the baseline due to the sail having the flattest (most plate like) setting, and allowed for clear quantification of individual and combined twist and camber effects. To vary the sail's camber, a sliding track-car at the aft of the boom was adjusted to alter the chord length at the foot of the sail by 10-mm (~1% of the foot length) increments (Fig. 5). There were also three reinforced holes (25 mm apart) along the leech at the foot of the sail. These holes provided options for connecting by pin to the track car and, by changing between the three holes, the sail's leech was tightened or loosened to vary sail twist (Fig. 5). For each test case, the six body-fixed forces and moments were measured twice at AOAs between 0° and 40°, and with a constant water velocity of $0.5\ m\ s^{-1}$.

**Table 2**
Five sail cases, encompassing low, medium and high combinations of twist and camber.

| Setting | Low camber | Medium camber | High camber |
|---|---|---|---|
| **Low twist** | Case 1 | | Case 3 |
| **Medium twist** | | Case 5 | |
| **High twist** | Case 7 | | Case 9 |

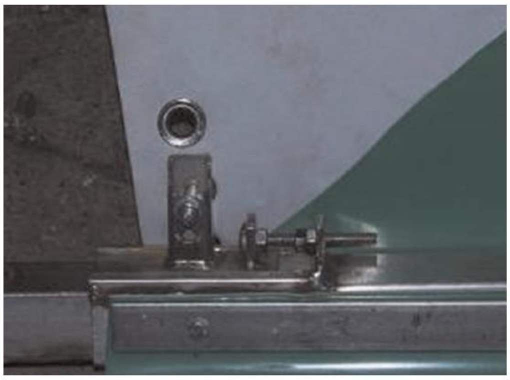

**Fig. 5.** Sliding track-car assembly at the aft-end of the boom enabling adjustment of the sail's camber and twist.

Prior to testing, the load cell (1100 N MC3A force and torque sensor) was calibrated and was zeroed in situ during static water. Data were recorded at 100 Hz for 10 s. The load cell was orientated

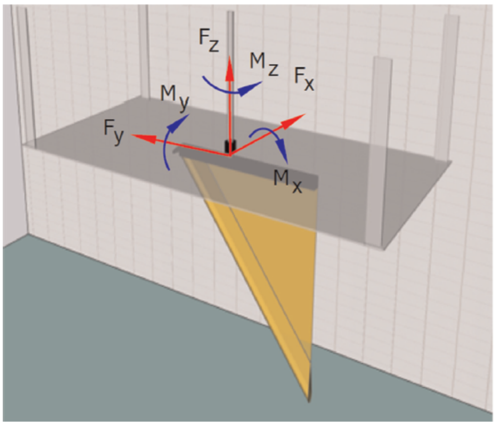


**Fig. 6.** Three-dimensional representation of the #1 sail and testing apparatus with the load-cell position/orientation and corresponding forces/moments indicated.

such that the *y*-axis force was aligned to the direction of the flow at 0° AOA (Fig. 4).

Additional data were obtained for a flat plate at AOAs between −90° and +90° to produce a crosstalk matrix for the load cell. The crosstalk matrix was derived from the flat-plate data by forcing the performance results to be both symmetrical about 0° AOA and a constant *z* force across the AOA range. This process formulated a matrix that corrected the load-cell output and produced realistic processed results for the sails. Eqs. (1) and (2) were applied to the corrected body-fixed forces to compute the respective lift and drag.

$$\text{Lift} = F_x \cos(\text{AOA}) - F_y \sin(\text{AOA}) \tag{1}$$

$$\text{Drag} = -F_x \sin(\text{AOA}) - F_y \cos(\text{AOA}) \tag{2}$$

The chord wise ($COP_y$) and span-wise ($COP_z$) centre of pressure locations at each AOA were estimated with Eqs. (3) and (4). The COP location results from Eqs. (3) and (4) are non-dimensional corresponding to the proportion of the foot-length from the front edge of the boom for $COP_y$ and the proportion of the sail height from the outer edge of the boom for $COP_z$.

$$COP_y = \frac{\left(\text{Sail}_L - \text{Cell}_y + \frac{M_z}{F_x}\right)}{\text{Sail}_L} \tag{3}$$

$$COP_z = \frac{-\left(\frac{M_y}{F_x} + \text{Cell}_D\right)}{\text{Sail}_H} \tag{4}$$

where $Sail_L$ is the foot length of the sail, $\text{Cell}_y$ is the distance from trailing edge to load-cell centre, $\text{Cell}_D$ is the distance from the outer edge of the boom to the load-cell centre, $\text{Sail}_H$ is the height of the sail arrangement, and *M* and *F* are corrected body-fixed moment and force respectively as per Fig. 6.

The flume tank generally provides steady and repeatable relative measurements. To demonstrate the general level of variance in the data, 95% confidence intervals for lift, drag and *L*/*D* at 20° AOA were estimated from the variance observed in the replicated measurements of body-fixed forces and using the rules for variance propagation given in Eq. (5) to calculate the associated variance in the flow-fixed forces and their ratio (*L*/*D*):

$$y = f(x_1, x_2) \quad \sigma_y^2 = \left(\frac{\delta f}{\delta x_1}\right)^2 \sigma_{x_1}^2 + \left(\frac{\delta f}{\delta x_2}\right)^2 \sigma_{x_2}^2 + 2\frac{\delta f}{\delta x_1}\frac{\delta f}{\delta x_2}\sigma_{x1}\sigma_{x2} \tag{5}$$

## 3. Results

The lift, drag and *L*/*D* results are presented in Fig. 7 for each tested combination of twist and camber for the #1 sail, with an overlay of the results for the #3 sail (Balash et al., 2015b) to facilitate comparison. Table 3 summarises the major hydrodynamic characteristics for both sails.

### 3.1. General lift, drag and L/D trends

For all cases, lift from the #1 sail linearly increased with AOA until the effects of flow separation caused a slowdown, with a maximum value at a stall angle of ~30°, and a decreasing lift thereafter. By comparison, the lift curves for the #3 sail had a more detailed structure with each having a major peak in lift at between 21° and 24°, and a secondary strengthening of lift at higher AOA (Table 3, Fig. 7). For cases 1 and 3, the #3 sail only generated similar lift to the #1 sail, despite having 20% more area; and for the other cases, where twist was introduced, the #3 sail produced generally less lift than the #1 sail, except at its stall AOA, where it had similar performance (Fig. 7, Table 3). Each of the drag responses had a continual increase with AOA. For all cases, the #1 sail generally had more drag than the #3 sail. Each #1 sail case showed a maximum *L*/*D* ratio between 3.7 and 4.1 at low AOAs between 6° and 10°, while for the #3 sail, the maximum *L*/*D* ranged between 4.0 and 4.7 at 10–16° (Table 3). Generally therefore, the #3 sail had 12.0% more maximum *L*/*D* at a 5° higher AOA.

Overall, the largest lift (42.5 N) produced by the #1 sail occurred for case 9 (high twist and high camber) at the stall angle of 30° (Table 3). Compared to baseline, case 7 (high twist) produced the smallest drag at the stall angle, whilst producing a similar increase in lift as the high-camber adjustment (case 3). The effect of camber on the performance of the #3 sail was similar, in that case 9 produced the largest lift, but at a lower stall angle of 24° and case 7 had a similar effect on drag; however, its effect on lift production at this stall angle was subdued for the #3 sail compared to the effect described above for the #1 sail.

### 3.2. Lift, drag, and L/D at the design angle of attack (20°)

At the design AOA of 20°, case 9 produced the best lift of 37.1 N for the #1 sail, which was 11.1% greater than for case 1 (Table 4). Compared to this baseline, there were lift differences of +5.2% and −0.3% for cases 3 (low twist, high camber) and 7 (high twist, low camber), respectively (Table 4). It appeared both twist and camber increased lift, when combined; but singly camber was the most effective, while twist actually slightly reduced lift at 20° in contrast to the strong improvement observed at 30° (the stall angle). For the #3 sail, case 3 rather than case 9 produced the best lift, and 12% more than baseline. Twist more substantially reduced lift at this AOA for the #3 sail, and did not work constructively with camber to produce lift as it did for the #1 sail (Table 4).

Across all five cases, the lowest drag for sail #1 at 20° AOA occurred for case 7 (Table 4). The drag force was 18.3% lower than for baseline, proving that including twist would decrease drag. However, the drag reduction was much less (only 3.7%) when high twist was combined with high camber (case 9). For the #3 sail, the lowest drag at 20° AOA also occurred for case 7 (22.0% reduction

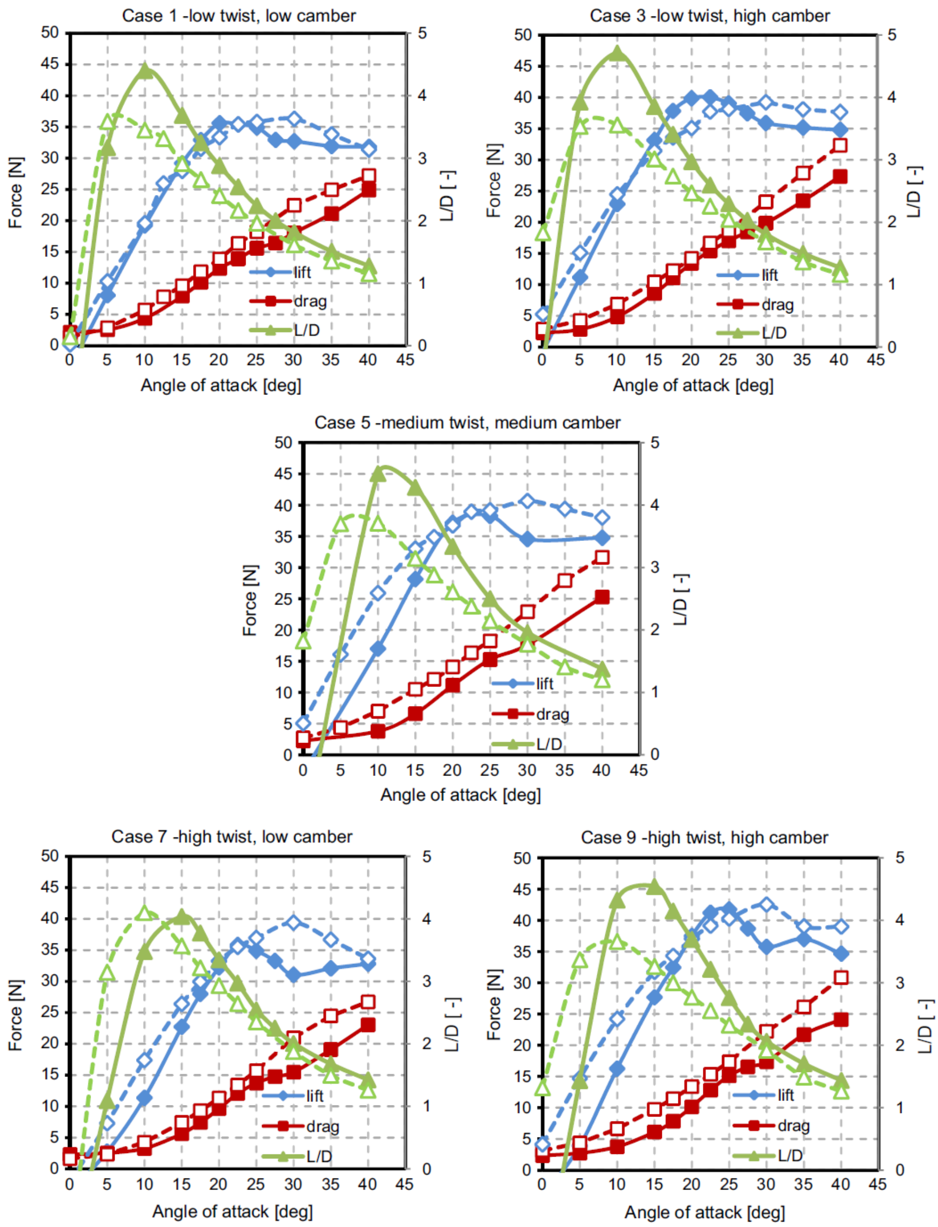


**Fig. 7.** Lift, drag and L/D ratio for each #1 sail case (dotted lines and open symbols) as per Table 2. Each #1 sail graph is overlaid on the equivalent #3 sail results for the same case (solid lines and symbols-(Balash et al., 2015b)).

compared to case 1), but the high twist combined with high camber (case 9) also produced a substantial drag reduction of 17.8%.

Because case 7 produced the smallest drag force for both sails at 20°, unsurprisingly this sail setting also produced very high *L*/*D* ratios (Table 4). For the #1 sail, case 7 produced the highest *L*/*D* (2.9) of all cases; while for sail #3, case 7 produced a *L*/*D* of 3.3, but case 9 produced the highest value of all (3.7) (Table 4).

**Table 3**
Major hydrodynamic characteristics of the #1 and #3 (Balash et al., 2015b) sails (cases are specified in Table 2).

| Characteristic | Sail #1 Cases | | | | | Sail #3 Cases | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | 1 | 3 | 5 | 7 | 9 | 1 | 3 | 5 | 7 | 9 |
| **Lift at stall [N]** | 36.3 | 39.2 | 40.7 | 39.4 | 42.5 | 35.6 | 40.0 | 38.3 | 36.0 | 42.0 |
| **Drag at stall [N]** | 22.5 | 23.3 | 22.9 | 21.0 | 22.2 | 12.4 | 15.0 | 15.0 | 12.1 | 15.0 |
| **AOA at stall [deg]** | 30 | 30 | 30 | 30 | 30 | 21 | 22 | 23 | 23 | 24 |
| **Maximum *L/D* [Dimensionless]** | 3.7 | 3.7 | 3.8 | 4.1 | 3.7 | 4.4 | 4.7 | 4.6 | 4.0 | 4.6 |
| **AOA at maximum *L/D* [deg]** | 6 | 7 | 7 | 10 | 9 | 11 | 10 | 12 | 16 | 13 |

**Table 4**
Effects of camber and twist on the characteristics of the #1 and #3 (Balash et al., 2015b) sails at the design AOA of 20°, with 95% confidence intervals. The baseline is case 1 (low twist and low camber).

| Characteristic | | #1 sail Cases | | | | | #3 sail Cases | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | 1 | 3 | 5 | 7 | 9 | 1 | 3 | 5 | 7 | 9 |
| **Lift at 20° AOA** | **[N]** | 33.4 ± 0.15 | 35.1 ± 0.04 | 36.7 ± 0.03 | 33.2 ± 0.02 | 37.1 ± 0.04 | 35.6 ± 0.15 | 39.9 ± 0.15 | 37.2 ± 0.09 | 32.2 ± 0.14 | 37.5 ± 0.09 |
| | **Δ from case 1[%]** | – | 5.2 ± 0.57 | 10.2 ± 0.52 | −0.3 ± 0.50 | 11.1 ± 0.55 | – | 12.0 ± 0.84 | 4.4 ± 0.69 | −9.4 ± 0.83 | 5.4 ± 0.67 |
| **Drag at 20° AOA** | **[N]** | 13.9 ± 0.20 | 14.2 ± 0.10 | 14.1 ± 0.08 | 11.3 ± 0.07 | 13.4 ± 0.09 | 12.4 ± 0.06 | 13.4 ± 0.06 | 11.1 ± 0.04 | 9.6 ± 0.06 | 10.2 ± 0.04 |
| | **Δ from case 1 [%]** | – | 2.2 ± 0.89 | 1.3 ± 0.83 | −18.3 ± 0.79 | −3.7 ± 0.87 | – | 8.6 ± 0.94 | −9.9 ± 0.79 | −22.0 ± 0.94 | −17.8 ± 0.77 |
| ***L/D* at 20° AOA** | **[Dimensionless]** | 2.4 ± 0.04 | 2.5 ± 0.02 | 2.6 ± 0.02 | 2.9 ± 0.02 | 2.8 ± 0.02 | 2.9 ± 0.02 | 3.0 ± 0.02 | 3.3 ± 0.01 | 3.3 ± 0.02 | 3.7 ± 0.02 |
| | **Δ from case 1 [%]** | – | 2.9 ± 0.16 | 8.7 ± 0.15 | 22.1 ± 0.16 | 15.3 ± 0.17 | – | 3.2 ± 1.22 | 15.9 ± 1.14 | 16.2 ± 1.50 | 28.3 ± 1.18 |

**Table 5**
Longitudinal centre of pressure ($COP_y$) movement (% of chord) when the AOA is reduced from 20° to 5° for #1 and #3 sails. Note positive is towards the trailing edge.

| Sail | Cases | | | | |
|---|---|---|---|---|---|
| | 1 | 3 | 5 | 7 | 9 |
| #1 | 3.4% | 9.4% | 12.8% | 5.1% | 15.3% |
| #3 | −9.2% | −1.0% | −2.5% | −13.2% | 31.7% |

### 3.3. Centre of pressure location and movement with respect to angle of attack

For all cases of the #1 sail, because the AOA increased from zero, $COP_y$ moved forward until reaching a minimum (position closest to the leading edge) at 17.5–25° AOA, before once again moving aft (increasing) with further AOA increase (Table 5, Fig. 8a). For the #3 sail, the behaviour of $COP_y$ between 5° and 20° was much more divergent between cases (Table 5, Fig. 8b).

Cases 1 and 7 (with low camber) produced a small net chord-wise movement of $COP_y$ of 3.4% and 5.1% towards the trailing edge with the AOA change from 20° to 5°, while the cases that included camber (3, 5 and 9) produced a larger aft $COP_y$ movement of up to 15.3% (Table 5). In contrast, cases 1 and 7 for the #3 sail exhibited strong forward movements of $COP_y$ with AOA (9.2% and 13.2% respectively), while the cambered cases tended to subdue the beneficial forward $COP_y$ movement, with case 9 exhibiting a strong aftward $COP_y$ movement of 31.7% instead (Table 5).

The span-wise centre-of pressure location ($COP_z$) for the #1 sail was relatively high on the sail (towards the tip) at low AOA, and moved towards the boom (sail-foot) as AOA increased (Fig. 9a). This was more evident for the untwisted cases (1 and 3), indicating the $COP_z$ movement towards the foot might be due to up wash generated stall over the top region of the sail. For the #3 sail, there was likely to be less up wash at the tip because of the lower mast-rake angle and less taper in the sail plan, and in conjunction with the large head twisting off under any significant loading naturally reduces the prospect of tip-sail and probably lead to the $COP_z$ not moving towards the foot appreciably as AOA increased (Fig. 8b). For the #3 sail though, there was a substantial $COP_z$ movement towards the foot at very low AOA for cases 7 and 9, probably due to the head of the sail becoming totally unloaded (Fig. 9b). This was a similar feature of the #1 sail, but it was very subdued because its head area was very small (Fig. 9a).

## 4. Discussion

Both sails displayed unique hydrodynamic effects in response to twist and camber being altered, but across all case results there was strong support for an optimal, generic operating AOA of ~20°. At higher AOAs there was a steep reduction in *L*/*D* (efficiency), and at lower AOAs a solid increase in *L*/*D* was severely negated by a very steep reduction in lift (spreading force). Above 20° there is very limited prospect to increase lift markedly, and any such benefit would not balance the associated rise in drag and reduction in efficiency. These findings can be discussed with respect to broad design-specific hydrodynamic responses, and used to recommend designs for future testing.

At the 20° operating AOA, introducing high twist (case 7) minimally affected the lift of sail #1 but decreased that of sail #3. Of greater interest, high sail twist decreased drag by 18.3% and 22% for the #1 and #3 sails, respectively. The most dominant effect of twist was the appropriate reduction in local AOA at the sail tip for the #1 sail considering the strong up-wash in that area due to the combined effects of mast rake and taper in the sail's plan form (Hurt, 1965). Strong twist in the batwing sails reduces the prospect of premature stall at the tips and produces a favourable orientation of the sail surface to produce efficient lift at higher AOAs. Adding twist also helps to reduce drag by preventing strong vortices occurring around the tip of the sails and the effects of finite

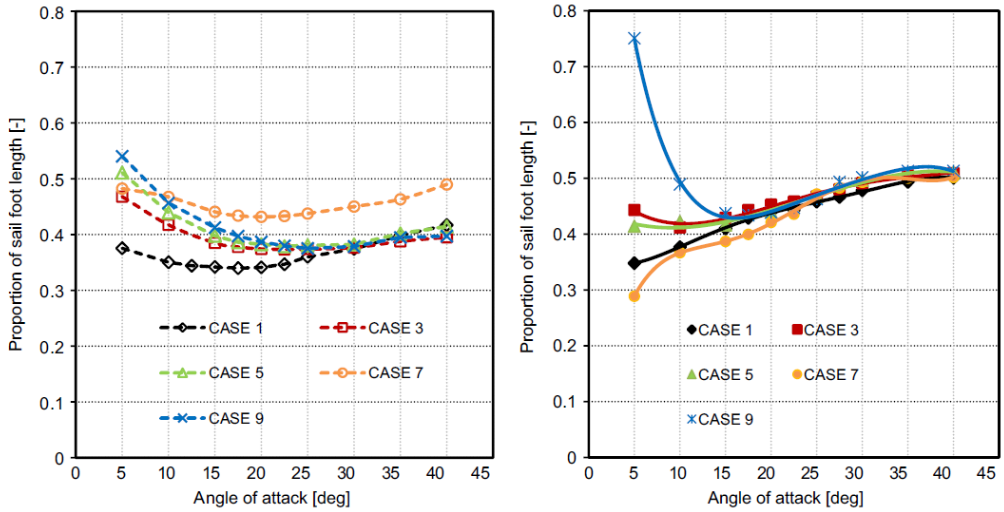


**Fig. 8.** Chord-wise centre of pressure location relative to the leading edge ($COP_y$) for sail #1 (a) and #3 (b) (Balash et al., 2015b).

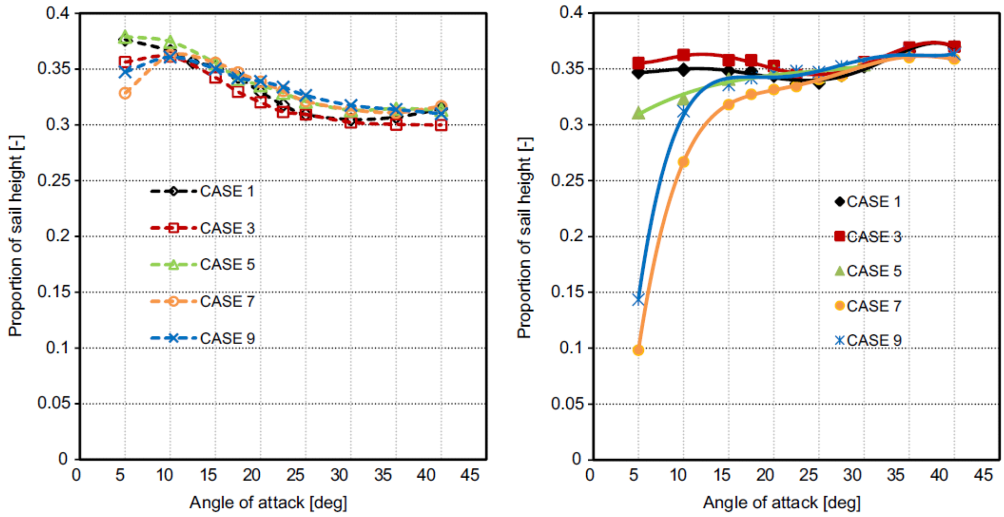


**Fig. 9.** Span-wise centre of pressure location relative to boom ($COP_z$) for sail #1 (a) and #3 (b).

aspect ratio by improving the distribution of lift along the span of the sail from boom to mast tip (ideally elliptical) (Abbott and Von Doenhoff, 1959). The larger head of the #3 sail also explains the greater drag reduction than for the #1 sail, but this resulted in lower lift than might be expected, or desirable.

Based on the larger surface area, the #3 sail theoretically should produce more lift and drag forces than the #1 sail, but this was contrary to the recorded data. One explanation for this anomaly is that the head in the #3 sail design was not able to be fixed at the same AOA as the lower part, which is attached to the boom, so the head induced additional twist in the upper region, and the relieved pressure gave rise to reduced hydrodynamic forces, particularly drag. As the head was relatively large compared to the entire sail, and because of the sail's flexible nature, there was a large area for additional twist to occur and therefore a substantial reduction in lift and drag.

With respect to $COP_y$ movement, twist on its own was benign for both sails. The observed continuous $COP_y$ movement towards the sail's leading edge for some cases as AOA decreased is an ideal situation because during towing the $COP_y$ shift will tend to align the sail back to the desired AOA, whereas $COP_y$ movement towards the trailing edge will enhance the sail's rotation towards low AOA and potentially cause the otter board to collapse. The otter board's orientation stability whilst trawling relates to the capacity of the design to resist disturbances (Sterling, 2010). The critical time for instability is during deployment, where the effects of surface waves on the otter board often cause marked disturbances to the desirable AOA. The major disturbances influencing the otter board whilst fishing on the seabed are generated by the ground forces on the base plate. The otter board typically responds to the disturbing forces by a yaw and roll rotation that is counteracted in part by the marginal movement of COP location. This stability feedback was strongest for cases 1 and 7 for both sails, indicating that camber had a detrimental influence. The $COP_y$ results also indicated that twist did not mediate camber because case 9 was inferior to case 3 in respect to $COP_y$ movement for both sails.

With respect to $COP_z$, movement across the AOA range, it was quite subtle except for a strong movement towards the foot at low AOA for the #3 sail with high twist. This effect could cause the otter board to roll (tip inwards) during trawling if it is disturbed to a low AOA by a seabed obstacle, and might help it ride over such obstacles.

Intuitively, any judgement regarding the optimal setting for each sail should be based on twist-and-camber effects across all aspects of otter-board performance, including: lift, drag, *L*/*D*, and COP movement with AOA. For the #1 sail there was a strong reduction in drag and improved efficiency from applying high twist (case 7) and clearly increased lift can be achieved by adding camber as well, without any substantial reduction in efficiency; but care would need to be taken with the effects of camber on AOA stability. Given the available information, a high-twist, low-camber setting is recommended for the #1 sail. Field trials are required to establish the amount of camber that can be applied before stability issues occur.

For the #3 sail, the combination of high twist and high camber (case 9) had very attractive lift-drag results. Isolated camber produced a strong gain in lift, but a solid increase in drag; while isolated twist greatly reduced drag, but with a moderate lift reduction; however when combined, they produced a moderate lift benefit with a large reduction in drag and the best *L*/*D* by a 12% margin. Unfortunately though, case 9 for the #3 sail had a very detrimental $COP_y$ response to reducing AOA, which would make it unlikely to be successful as a practical batwing setting. For this reason, case 5 is the recommended setting because it had an acceptable $COP_y$ response to AOA and maintained a reasonably high *L*/*D*.

Given the favourable hydrodynamic performance of both sails, the tested designs should now be subjected to more extensive commercial fishing trials. In particular, the #1 sail could be a coherent option for simple, small-scale gear used in sampling applications or fisheries operating in developing economies, while the more complex battened #3 design would be beneficial for larger-scale operations (~9-m headline trawls).

Because otter boards contribute up to 30% of total trawl-system drag, a correctly rigged pair of batwings should provide 10–20% drag savings, depending on trawl configurations, while at the same time limiting bottom contact and habitat impacts. Furthermore, if batwing otter boards are combined with modern, hydrodynamically effective trawls such as the "W" trawl (Balash et al., 2015a), the entire system might return drag savings of more than 30%. The results also encourage the development of batwing technologies for the large-scale end of the spectrum, where multiple-sail configurations involving one or two masts are proposed for the production of large hydrodynamic forces in medium to large sized industrial trawl gear.

## 5. Conclusions

The present work analysed the hydrodynamic performance effects of twist and camber in two simple sails through experimental testing in the flume tank over a range of AOA. The tested sails were designed for small (#1 sail) and small-medium sized trawl gear (#3 sail). The following conclusions were drawn from the work:

- Camber increases lift whereas twist increases efficiency.
- For all camber/twist combinations, a 20° AOA is optimal; being a compromise between lower AOA for high *L*/*D* ratio and greater AOA for high spreading force.
- An increase of mast rake angle from 30° to 45° reduces *L*/*D* at 20° AOA by 12% for the optimal cases.
- Stall angle increases for the higher rake angle, despite the associated sail having the higher aspect ratio of the two sails.
- Optimum performance and stability characteristics can be achieved with high twist and low camber for the #1 sail, and medium twist and medium camber for the #3 sail.
- The achieved L/D of ~3 for these twist/camber settings is ~3 times greater than for contemporary otter boards, which implies up to 20% drag reduction for the entire system including the trawl and vessel.
- Due to the favourable results obtained for both sails, field trials for the simple #1 sail should now occur to develop a low-cost implementation of the batwing otter board technology for small-scale gear.

## Acknowledgements

This study was funded by the New South Wales Department of Primary Industries and the Australian Fisheries Research and Development Corporation (FRDC; Grant no. 2011/010 – www.frdc.com.au). The Australian Maritime College of the University of Tasmania provided the flume tank and associated resources. Funding for developing and implementing the batwing otter board was provided by the World Wildlife Fund PA 01, PA 17; Envirofund 62463; and the FRDC (Grant nos 2004/060 and 2008/079).

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**Appendix 20.** Broadhurst, M., Sterling, D. and Millar, R. 2013. Progressing more environmentally benign prawn-trawling systems by comparing Australian single- and multi-configurations. Professional Fishing Association Magazine, December 2013: 12–13.

# Reducing the environmental impacts and improving the profitability of prawn trawling

The following is a summary of a recent experiment completed by NSW DPI as part of a four-year FRDC-funded project (no. 2011/010, entitled 'Reducing the environmental impacts and improving the profitability of prawn trawling through a structured framework of anterior gear modifications'). The formal results from the project will be provided to industry at the end of 2015.

## 'Configuring the mesh size, body taper and wing area of prawn trawls to reduce environmental impacts'

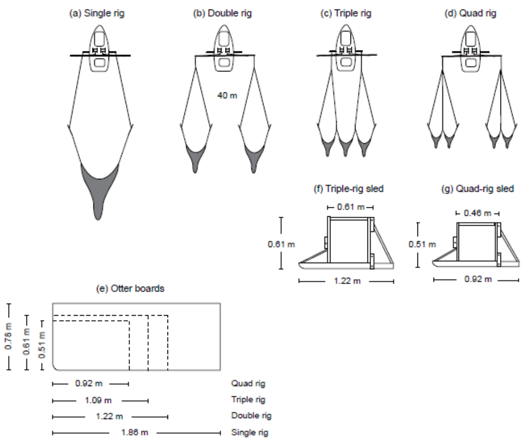
*By Matt Broadhurst, Dave Sterling and Russell Millar*

### Progressing more environmentally benign prawn-trawling systems by comparing Australian single- and multi-configurations.

Prawns are important to commercial fisheries throughout Australia, with 13 key species targeted by some 1300 vessels (~8–25 m) in 13 separately managed fisheries; towing either a single trawl, or two, three or four trawls in parallel. All trawls are fished on the seabed, and opened horizontally using complex systems of hydrovanes (termed 'otter boards') and sleds. Australian prawn-trawl fisheries are quite diverse in terms of the targeted species and legislated gear configurations (including minimum and maximum mesh sizes and headline lengths), but like in many overseas fisheries, they all have two common environmental issues, including poor (1) species and size selectivity and (2) high energy intensities. Further, in some fisheries there is an additional concern regarding (3) perceived habitat impacts. Over the past 30 years, attempts have been made to independently address these three issues, although by far the greatest effort has focused on modifying trawls to include physical bycatch reduction devices (BRDs), designed to exclude unwanted fish (i.e. 1 above).

While BRDs have mitigated what is perhaps the most important environmental concern associated with prawn trawling, none are 100% effective, nor do they address the high energy intensities or the potential habitat impacts of trawls (2 and 3 above). Also, in many prawn-trawl fisheries, there has been reluctance by industries to adopt BRDs that have had few practical benefits. An alternative resolution approach might involve attempts at broadly addressing aspects of all three environmental issues (especially that of most concern to fishers – high fuel costs) by firstly comparing existing categories of trawling configurations to gauge the limits of what is possible within the current technology, before complicating additions or adjustments are made. Such a framework makes sense, not only in terms of practicality, but also legislation, because simply choosing a conventional configuration that has fewer environmental impacts fits more easily within existing policy than completely new gear.

As part of an ongoing four-year project, this study aimed to further investigate the potential for the above benefits by comparing single-, double-, triple- and quad-rigged prawn trawls (all with the same cumulative headline length of 14.63 m) at one location (the Clarence River) in NSW. The chosen trawl configurations were representative of those used throughout Australia, and all were optimised to fit the same vessel. Over six weeks, each configuration was tested a total of 36 times (in 35-min tows), with various relevant technical (e.g. drag, fuel used, horizontal-net spread and towing speed) and biological (numbers, weights and sizes of catches) data recorded. The relative performances of the four trawling configurations reflected a complex array of interacting factors, but broadly the incremental magnitudes of differences decreased with an increasing number of nets. The single trawl had the least total bottom contact, but the greatest drag, lowest horizontal spread ratio (SR – i.e. horizontal opening to headline length of 63.50%) and required the most fuel to tow (an average of 2.82 L per ha trawled). Further, this system caught significantly more yellowfin bream, and fewer (but larger) school prawns than the multi-trawl configurations. Compared to single rig, the double rig had a greater SR (68.76%) and was easier to tow (2.53 L per ha trawled). However, triple- and quad-rigs similarly achieved the greatest SRs (75.46 and 74.37%) and at lower drag and fuel consumptions (2.08 and 2.22 L per ha trawled,




respectively). Providing effort is regulated, the latter two configurations, but especially triple rig (which, owing to smaller and fewer otter boards had relatively less total bottom contact), could represent the most suitable configuration from which to progress modifications to reduce the environmental impacts of prawn trawling. Such modifications could include more hydrodynamic otter boards and netting materials, different ground gear configurations and net designs. These, and other, changes will be assessed as part of ongoing work.

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Fisheries Research
For further information on reducing the environmental impacts
and improving the profitability of prawn trawling.
Contact Matt Broadhurst at matt.broadhurst@dpi.nsw.gov.au

**Appendix 21.** McHugh, M., Broadhurst, M., Sterling, D. and Millar, R. 2014. Comparing otter boards to improve fuel efficiency. Queensland Seafood, 4: 20–21.

BOATS & GEAR

# Comparing otter boards to improve fuel efficiency

**An experiment has been conducted to compare otter boards – three conventional designs and the new "batwing" design – to try to improve fuel efficiency.**

THIS article summarises the recent experiment by the NSW Department of Primary Industries (DPI) as part of a four-year project* funded by the Fisheries Research & Development Corporation. The formal results from the project will be provided to industry at the end of 2015.

Prawns are targeted throughout the world's tropical and temperate regions, mostly using small vessels (smaller than 25 metres) towing multi-net trawl systems spread by either beams or, more commonly, otter boards.

While there is considerable variability among otter-board designs, all encompass a substantial proportion of the entire trawl-system weight (to ensure sufficient seabed contact) and are orientated at an angle to the tow direction (termed the angle of attack – AOA).

The AOA means that otter boards create substantial drag, which can account for 30 to 40% of the total system.

The strong contribution of otter boards to drag means that even subtle variations and refinements to designs have the potential to considerably improve overall prawn-trawl efficiencies, and ultimately the quantity of fuel used by trawlers.

Despite this, and while substantial theoretical work has been done, very few studies have compared the relative engineering and catching performances of existing prawn-trawl otter boards, nor subtle refinements, during conventional fishing.

As part of a larger FRDC-funded project, we sought to contribute towards the limited information concerning otter-board performances during three experiments in the Clarence River prawn-trawl fishery, NSW.

Over 16 days of fishing, we compared a novel, hydrodynamic otter board termed the 'batwing' (comprising a sled-and-sail assembly, configured to operate at 20° AOA, and with minimal bottom contact) against three conventional designs (termed the 'flat-rectangular'; 'kilfoil' and 'cambered' otter boards) with AOAs between ~30 and 40° (Figure 1a–d).

All otter boards had the same attachment height for the trawl headlines (Figure 1). Using paired trawls (7.35-m headlines and 2.89 m sweeps), the batwing otter boards were first tested against all other designs (30-min deployments over 12 days) and then just the flat-rectangular design (50-min deployments over four days).

Compared to the conventional

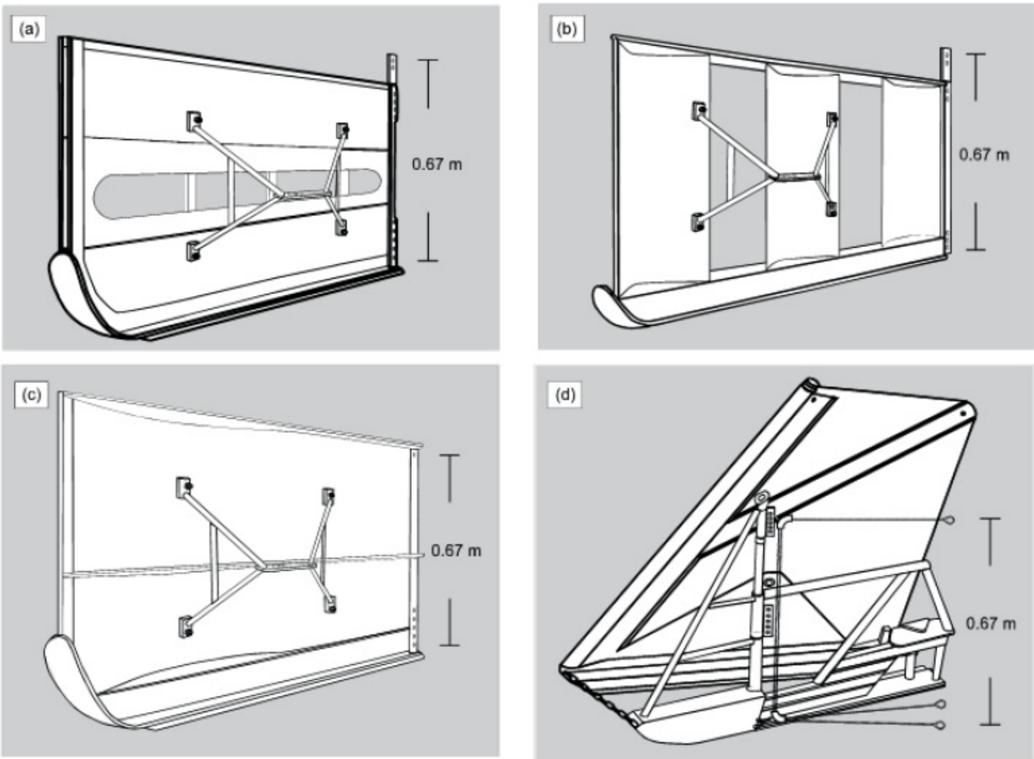


**Figure. 1.** *Three dimensional representation of the (a) flat rectangular (52.5 kg, 1.39 × 0.61 m), (b) kilfoil (63.0 kg, 1.25 × 0.63 m), (c) cambered (53.0 kg, 1.08 × 0.73 m ) and (d) batwing (60.7 kg, 1.12 × 1.23 m) otter boards tested in the experiments.*

**Figure 2.** *The batwing otter boards being deployed.*

| | Otter boards | | | |
|---|---|---|---|---|
| | Flat-rectangular | Kilfoil | Cambered | Batwing |
| **Experiment 1** | | | | |
| Combined wing-end spread for both trawls (m) | 10.16 | 10.34 | 10.26 | 10.20 |
| Otter-board angle of attack (o) | 32.83 | 30.58 | 38.62 | 20.00 |
| Drag (kg) | 503.14 | 529.88 | 528.92 | 432.66 |
| Fuel rate (L hour–1) | 11.64 | 12.26 | 12.24 | 10.00 |
| Fuel intensity (L hectare–1) | 2.57 | 2.66 | 2.68 | 2.20 |
| **Experiment 2** | | | | |
| Combined wing-end spread for both trawls (m) | 10.34 | – | – | 10.24 |
| Otter-board angle of attack (o) | 33.71 | – | – | 20.00 |
| Drag (kg) | 536.28 | – | – | 455.86 |
| Fuel rate (L hour–1) | 12.42 | – | – | 10.56 |
| Fuel intensity (L hectare–1) | 2.33 | – | – | 2.00 |

**Table 1.** *Mean estimated engineering parameters, and fuel rates and intensities for double-rigged prawn trawls in the Clarence River. The data for experiment 1 were derived using identical trawls made from 42-mm mesh, while in experiment 2, trawls made from 32-mm mesh were used.*

otter boards, the pair of batwings was considerably easier to tow (Table 1). More specifically, for the same wing-end spread, the batwing pair required 2.20 L of fuel per hectare trawled, which was between 14 and 18% less than the other otter boards (Table 1).

These data mean that for the trawler examined (10 m with an 89-kw engine) substituting conventional otter boards with the batwings on both trawls would equate to savings of between approximately 10 and 14 l per day (assuming 6 × 1 h deployments) and ~1,750 l less fuel over the fishing season (70 l per week × 25 weeks) (Table 1).

In terms of catches, the trawls with the batwing otter boards caught fewer targeted school prawns in experiment 1, but this was attributed to some confounding effects of rigging which were subsequently rectified in experiment 2, with no significant difference compared to trawls spread by the flat-rectangular design.

In experiment 1, among the conventional otter boards, the cambered design caught up to 13% more school prawns; possibly because the greater solid profile deflected more prawns into the trawl. There were no differences in the catches of unwanted fish (which were very low) between trawls rigged with any of the otter boards.

The results reaffirm that because otter boards contribute towards a large proportion of total system drag, their appropriate configuration is essential to maximise the efficiency of prawn trawls. This requirement will become ever more important as fuel costs increase.

Concepts like the batwing offer substantial benefits in terms of fuel savings, and along with subtle modifications to conventional designs, are being further refined and tested as part of ongoing research funded by NSW DPI and FRDC and in association with Sterling Trawl Gear Services.

**Matthew McHugh, Matt Broadhurst, Dave Sterling and Russell Millar**

*The project is FRDC Project No. 2011-010: "Reducing the environmental impacts and improving the profitability of prawn trawling through a structured framework of anterior gear modifications".

**Appendix 22.** Broadhurst, M., Sterling, D. and Millar, R. 2015. Configuring the mesh size, body taper and wing area of prawn trawls to reduce environmental impacts. Professional Fishing Association Magazine, February 2015: 6–7.


# Prawn Trawling

The following is a summary of a recent experiment completed by NSW DPI as part of a four-year FRDC-funded project (no. 2011/010, entitled 'Reducing the environmental impacts and improving the profitability of prawn trawling through a structured framework of anterior gear modifications'). The formal results from the project will be provided to industry at the end of 2015.

**'Configuring the mesh size, body taper and wing area of prawn trawls to reduce environmental impacts'**
*By Matt Broadhurst, Dave Sterling and Russell Millar*

Prawn trawling occurs throughout inshore waters of many tropical and temperate countries, and is an important source of income for many coastal communities. More than 100 species are targeted using a variety of trawl designs and methods of operation. While there are fishery-specific management concerns, virtually all prawn fisheries are characterized by the same two broad environmental issues.

The main concern is that, because of their small meshes and use in areas characterised by large abundances of small organisms, prawn trawls often catch non-target individuals (especially fish), termed 'bycatch'. Over the past two decades, this issue has been partially addressed via the installation of bycatch reduction devices (BRDs) into the posterior section (termed the 'codend') of trawls. Such modifications have dramatically improved selectivity, but none are 100% effective, and in some fisheries, large numbers of unwanted organisms are still caught and discarded.

The second, more recent growing concern associated with prawn trawls is their relatively poor efficiency. Trawling produces a lot of drag, which requires substantial energy. Rising fuel costs have led to an increasing impetus to reduce the inherent engineering deficits of this fishing method.

Conceivably, the above environmental concerns associated with prawn trawling could be concurrently addressed via modifications to the anterior sections of trawls; primarily because this area ultimately (1) is responsible for much of the drag, and (2) regulates what is directed into the codend. However, very little relevant research has been done. The aim of this study was to help address this shortfall, by assessing the importance of mesh size, trawl side taper (and therefore the total length) and wing depth (and therefore the amount of netting) in a common design of trawl body. The work was done in Lake Wooloweyah and the Clarence River, but the results have implications for other local and international prawn-trawl fisheries.

Five trawls were tested. The first trawl was made from 41-mm mesh (18 ply twine) and represented conventional designs (termed the '41 1N3B deep-wing'), while the remaining four trawls were all made from 32-mm mesh (12 ply) and differed only in their side tapers (1N3B–~28o to the tow direction vs 1N5B–~35o), and wing depths ('deep'–97 T vs 'shallow'–60 T). All trawls had 'Nordmøre-grid' BRDs installed, and each was deployed 38 times.

There were incremental drag reductions (and therefore fuel savings – by up to 18 and 12% per hour and hectare trawled) associated with reducing twine area (via either of the assessed modifications), and subsequently reducing otter-board area. Side taper and wing depth had interactive and varied effects on bycatch reduction, but compared to the conventional 41 1N3B deep-wing trawl, the 32 1N5B shallow-wing trawl (i.e. the design with the lowest twine area) caught significantly less unwanted fish (by up to 57%); which was explained by the shorter trawl allowing more individuals to swim forward and escape, either from the mouth of the trawl or via the Nordmøre-grid. In most cases, all small-meshed trawls also caught more school prawns (including both small and commercial-sized individuals) than the conventional 41-mm trawl.

The results observed here have implications for on-going research. Clearly, determining the most appropriate mesh size and ideally ensuring consistent openings throughout the trawl is an important precursor to other modifications. We showed that it is possible to reduce mesh size, but improve species selection through other changes, presumably because mesh openings mostly determined the selectivity of the targeted school prawns, whereas fish were more affected by changes in trawl geometry. Based on the mean sizes of school prawns retained, the 32-mm mesh we examined is too small. However, it should be possible to increase mesh size slightly to somewhere less than 41-mm, while still using a steep body taper to reduce fish bycatch, and with the least amount of twine area to minimise otter-board area and drag. These results support a philosophy of first optimising mesh size as a precursor to other anterior changes in other prawn-trawl fisheries.

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**Appendix 23.** McHugh, M.J., Broadhurst, M.K., Skilleter, G. and Sterling, D.J. 2015. An angle to address benthic-trawl impacts. Oral presentation at the AMSA annual conference, July 2015 in Geelong, Australia.

An angle to address benthic-trawl impacts

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Benthic trawls are spread by rectangular hydro-vanes (called 'otter boards') which are heavy (up to 75% of the total system weight) and leave discernible marks on the substrate. Lowering the otter-board base-plate angle of attack (AOA; conventionally between 30 and 40°) is one mechanism for potentially reducing habitat impacts among demersal trawls, and with concomitant drag (and fuel) benefits, but there are few quantitative assessments. To address this information deficit, we assessed a novel prawn-trawling otter board, termed the 'batwing' (rigged with a base plate at 0° AOA) against a conventional flat-rectangular design (base plate at 35° AOA) for relative drag, catchability and habitat impacts. The batwing maintained spreading force with no significant effects on catches, but had up to 18% less drag and mobilised significantly less benthic material (empty shells, *Anadara trapezia* and *Spisula trigonella* and timber fragments) at rates closely correlated to the reduction in base-plate bottom contact (by 87%). Further, of the shells that were displaced, the batwing damaged proportionally fewer. The latter results have encouraging implications for habitat preservation. Specifically, if a typical Australian prawn trawler towing two trawls had its four conventional otter boards (i.e. each with a length of 2.13 m at 35° AOA) replaced with batwings, then the bottom contact of heavy steel (>250 kg being dragged obliquely) would be reduced by ~0.190 km$^2$ (>10 times the ANZ Stadium oval) over one fishing night (8-hours trawling). If only 110 vessels (~10% of the national prawn trawling fleet) used the batwings for 120 nights, the total reduction in bottom contact would amount to an area greater than the Australian Capital Territory (2,358 km$^2$). The associated fuel savings (up to 18%) would also be considerable, considering that a prawn trawler can use in excess of 60 l per hour while fishing. While further refinements are required, reducing otter-board AOA via designs like the batwing demonstrates the utility of simple modifications to prawn-trawling systems for holistically addressing environmental inefficiencies.

**Appendix 24**. Lay summaries of scientific outputs from FRDC Project 2011/010: Reducing the environmental impacts and improving the profitability of prawn trawling through a structured framework of anterior gear modifications

**Effects of otter boards on catches of an Australian penaeid trawl**

*Lay summary*

Bottom trawling is an old, but very common, commercial fishing method used throughout the world to target various species of benthic fish and crustaceans, and especially penaeid prawns. Prawn-trawl configurations typically involve multiple nets (i.e. double-, triple- or quad-rigs) that are attached to hydro vanes, or 'otter boards' and towed behind a vessel. The otter boards comprise a substantial weight (up to 40%) of the entire trawl configuration and are orientated at an angle to the tow, so that their drag horizontally spreads the nets.

While so-called 'otter trawls' are quite effective at catching prawns (and other benthic organisms), in some countries there are concerns over their perceived habitat impacts, and they are not particularly fuel efficient. In recent years, rising fuel costs have prompted efforts at improving the efficiency of otter trawling, and because otter boards contribute towards much of the total drag, their modification is a logical starting point. There are several options for reducing otter-board drag, ranging from simply lower angles of attack and greater aspect ratios of traditional configurations, to completely new, more hydrodynamic designs. Alternatively, in some small-scale fisheries, simply replacing otter boards with a horizontal beam and sleds (which are towed parallel to the vessel) should also reduce drag.

However, one important consideration associated with modifying or removing otter boards is that they represent a considerable percentage of the trawl bottom contact and are angled to direct water towards the trawl. These are two factors that could affect the catches of prawns. Understanding the contribution of otter boards to prawn catches is important, since to encourage the adoption of more hydrodynamic, fuel efficient, and environmentally benign trawling systems, there may be some requirement for compensatory adjustments to other trawl parameters to maintain catches.

This study aimed to contribute towards the limited available scientific data in this field, by determining the importance of otter boards on catches of school prawns in Lake Wooloweyah, NSW. Two identical trawls were separately and alternately attached behind either conventional otter boards or a beam assembly (6-m in length) and simultaneously towed (in a double rig) by a local trawler for fifty-one 40-min hauls. Information was collected on the horizontal trawl openings (and associated area trawled), the drag of each configuration and the catches of school prawns and unwanted fish.

The two spreading systems caused similar trawl openings (~ 4.4 m between the wing ends). But, compared to the otter trawl, the beam trawl had significantly less drag (by ~10%) and also caught ~33% fewer school prawns per hectare trawled. The difference in prawn catches was attributed to the efficiency of the otter boards for disturbing school prawns out of the substrate and directing them towards the trawl mouth. The beam trawl also caught ~80% fewer individuals of the most abundant fish (southern herring), which was at least partially attributed to the beam directing some individuals away from the trawl mouth.

While the large reduction in prawn catches by the beam trawl tested here would preclude its use in Lake Wooloweyah, simple modifications, like increasing the foot-rope length to compensate for the loss of the otter boards and making the beam more hydrodynamic, might increase the catches of prawns, and lower drag (while still catching few fish). Alternatively, if otter boards remain but modifications to improve their hydrodynamics concomitantly reduce bottom contact, then adjustments to other trawl parameters might also be required to offset any loss of the targeted school prawns.

**Relative engineering and catching performances of paired penaeid-trawling systems**

*Lay summary*

Penaeid prawns are very important to the commercial fisheries of many countries. More than 100 species are targeted using various stationary and mobile fishing gears, although most of the global catch is harvested by otter trawling, which involves one or more funnel-shaped nets that are towed and held open by hydro vanes (called 'otter boards').

All prawn-trawl fisheries have specific management issues and challenges, but at a broad level, the key environmental concerns of most can be simplified as: poor (1) species and size selectivity (i.e. discarded bycatch) and (2) fossil-fuel efficiencies, and (3) unwanted benthic habitat impacts. Over the past 30 years, various attempts have been made to independently address these three issues, although by far the greatest efforts have focused on modifying trawls to include physical bycatch reduction devices (BRDs), designed to exclude unwanted fish (i.e. 1 above).

While BRDs have mitigated what is perhaps the most important environmental concern associated with prawn trawling, none are 100% effective and few, if any, also address either the poor fuel efficiencies or the potential habitat impacts of trawls (2 and 3 above). Also, in many prawn-trawl fisheries, including those in Australia, there has been reluctance by industries to adopt BRDs that have had few perceived practical benefits.

An alternative resolution approach might involve attempts at broadly addressing aspects of all three environmental issues (especially that of most concern to fishers – poor efficiencies) by firstly comparing existing categories of trawling configurations to gauge the limits of what is possible within the current technology, before complicating additions or adjustments are made. Such a framework makes sense, not only in terms of practicality, but also legislation, because simply choosing a conventional configuration that is inherently more environmentally benign fits more easily within existing policy than completely new gear.

The aim of this study was to investigate the utility of such an approach by comparing the relative engineering and catching performances of two mechanisms for spreading paired trawls in the Clarence River. Identical, twin trawls (7.35-m headline) were alternately towed in a "double rig" (comprising four otter boards; two for each trawl) with either 18- or 36-m bridles ("short-" and "long-" double rigs) and in a "dual rig" (36-m bridles with the trawls separated by an otter board, sled and then another otter board).

Across similar towing speeds, the average horizontal trawl openings were greatest in the long-double (4.51 m each), followed by the short-double (4.28 m) and dual (3.85 m) rigs. But, compared to both double rigs, the dual rig required 24 and 20% less towing force and fuel and caught significantly fewer (by ~60%) small mulloway per hectare of trawl-mouth contact.

The dual rig also caught proportionally larger school prawns, but fewer by number than the double rigs. These two effects on prawn catches were attributed to the otter boards and their efficiency for disturbing small school prawns out of the substratum and directing them towards the trawl mouth.

The results suggest that while removing two otter boards reduces benthic contact, towing force, fuel consumption and bycatch, there is some cost to the catches of school prawns. However, simple adjustments to the dual rig, including possibly longer otter boards, and/or slightly wider trawls might improve prawn catches, while still maintaining the other associated environmental benefits. The data also support a framework of progressing simple, applied solutions to holistically address all of the key perceived environmental concerns associated with prawn trawling.

**Progressing more environmentally benign penaeid-trawling systems by comparing Australian single- and multi-configurations**

*Lay summary*

Prawns are important to commercial fisheries throughout Australia, with 13 key species targeted by some 1300 vessels (~8–25 m) in 13 separately managed fisheries; towing either a single trawl, or two, three or four trawls in parallel. All trawls are fished on the seabed, and opened horizontally using complex systems of hydrovanes (termed 'otter boards') and sleds.

Australian prawn-trawl fisheries are quite diverse in terms of the targeted species and legislated gear configurations (including minimum and maximum mesh sizes and headline lengths), but like in many overseas fisheries, they all have two common environmental issues, including poor (1) species and size selectivity and (2) high energy intensities. Further, in some fisheries there is an additional concern regarding (3) perceived habitat impacts.

Over the past 30 years, attempts have been made to independently address these three issues, although by far the greatest effort has focused on modifying trawls to include physical bycatch reduction devices (BRDs), designed to exclude unwanted fish (i.e. 1 above). While BRDs have mitigated what is perhaps the most important environmental concern associated with prawn trawling, none are 100% effective, nor do they address the high energy intensities or the potential habitat impacts of trawls (2 and 3 above). Also, in many prawn-trawl fisheries, there has been reluctance by industries to adopt BRDs that have had few practical benefits.

An alternative resolution approach might involve attempts at broadly addressing aspects of all three environmental issues (especially that of most concern to fishers – high fuel costs) by firstly comparing existing categories of trawling configurations to gauge the limits of what is possible within the current technology, before complicating additions or adjustments are made. Such a framework makes sense, not only in terms of practicality, but also legislation, because simply choosing a conventional configuration that has fewer environmental impacts fits more easily within existing policy than completely new gear.

As part of an ongoing four-year project, this study aimed to further investigate the potential for the above benefits by comparing single-, double-, triple- and quad-rigged prawn trawls (all with the same cumulative headline length of 14.63 m) at one location (the Clarence River) in NSW. The chosen trawl configurations were representative of those used throughout Australia, and all were optimised to fit the same vessel. Over six weeks, each configuration was tested a total of 36 times (in 35-min tows), with various relevant technical (e.g. drag, fuel used, horizontal-net spread and towing speed) and biological (numbers, weights and sizes of catches) data recorded.

The relative performances of the four trawling configurations reflected a complex array of interacting factors, but broadly the incremental magnitudes of differences decreased with an increasing number of nets. The single trawl had the least total bottom contact, but the greatest drag, lowest horizontal spread ratio (SR – i.e. horizontal opening to headline length of 63.50%) and required the most fuel to tow (an average of 2.82 L per ha trawled). Further, this system caught significantly more yellowfin bream, and fewer (but larger) school prawns than the multi-trawl configurations. Compared to single rig, the double rig had a greater SR (68.76%) and was easier to tow (2.53 L per ha trawled). However, triple- and quad-rigs similarly achieved the greatest SRs (75.46 and 74.37%) and at lower drag and fuel consumptions (2.08 and 2.22 L per ha trawled, respectively).

Providing effort is regulated, the latter two configurations, but especially triple rig (which, owing to smaller and fewer otter boards had relatively less total bottom contact), could represent the most suitable configuration from which to progress modifications to reduce the environmental impacts of prawn trawling. Such modifications could include more hydrodynamic otter boards and netting materials, different ground gear configurations and net designs. These, and other, changes will be assessed as part of ongoing work.

**Short *vs* long penaeid trawls: effects of side taper on engineering and catching performances**

*Lay summary*

Prawns form the basis of important fisheries throughout estuaries and coastal areas in many tropical and temperate countries. More than 100 species are targeted using various fishing gears, although much of the total catch comes from ‘otter trawls’, which comprise a funnel-shaped net made from small mesh that is towed along the sea bed and horizontally spread using hydro vanes (called ‘otter boards’). Historically, this type of fishing gear has raised environmental concerns throughout most areas of its operation.

The main concern is that, because of their small meshes and use in areas characterised by large abundances of small organisms, prawn trawls often catch non-target individuals (especially fish). Over the past two decades, this issue has been partially addressed via the installation of bycatch reduction devices (BRDs) into the posterior section (termed the ‘codend’) of trawls. Such modifications have dramatically improved selectivity, but none are 100% effective, and in some fisheries large numbers of unwanted organisms are still caught and discarded.

A second, more recent growing concern associated with prawn trawls is their relatively poor efficiency. Trawling produces a lot of drag, which requires substantial energy. Rising fuel costs, combined with concerns over carbon emissions, have led to an increasing impetus to reduce the inherent engineering deficits of this fishing method.

Conceivably both of the above environmental concerns associated with prawn trawling could be addressed via modifications to the anterior sections of trawls; primarily because this area ultimately (1) is responsible for much of the drag, and (2) regulates what is directed into the codend. However, very little relevant research has been done. The aim of this study was to help address this shortfall, by assessing the importance of simply varying the taper (and therefore the total length and the amount of netting) in a common design of trawl body made with either two or four panels. The work was done in the Clarence River, but the results have implications for other local and international prawn-trawl fisheries.

Four trawls (called the '1N2B two-seam', '1N2B four-seam', '1N5B two-seam' and '1N5B four-seam trawls') were constructed. All trawls were identical except two were made with shallow tapers ($25^{o}$ to the direction of towing and total lengths of 10.4 m), while the other two were steeper and shorter ($35^{o}$ and 6.8 m). For each taper design, one of the trawls was made using four panels, and the other using two (to encompass variability in conventional construction). The trawls were tested against each other during several days fishing and data collected on their associated horizontal spread, drag and catches.

Irrespective of the number of panels, compared to the long, shallow-tapered 1N2B trawls, the shorter, steeper-tapered 1N5B designs achieved significantly greater predicted horizontal spreads (4.7–5.6%), while reducing drag (up to 4.3%) and also the numbers (per hectare trawled) of one abundant fish species (southern herring) by up to 66%. However, catches of the targeted school prawns (per hectare trawled) were also significantly lower in both of the 1N5B trawls (by up to 50%; and biased towards smaller individuals).

The catch reductions were attributed to the shorter, steeper-tapered trawl bodies increasing the probability of both fish and prawns encountering open meshes and/or allowing southern herring to swim forward and escape through the mouth of the trawl. Although the loss of school prawns was economically unacceptable for the Clarence River fishery, catches could be improved simply by reducing the mesh (42 mm) to a more appropriate size while potentially still maintaining the inherent engineering and selectivity benefits of using short trawls. The utility of this and other simple modifications to anterior trawl design will be tested as part of ongoing research.

## Engineering and catch implications of spread ratio on a penaeid trawl

*Lay summary*

Prawn trawling forms the basis of important artisanal and industrial fisheries in many tropical and temperate countries. While these fisheries use many different designs and configurations of trawls, nearly all are characterised by the same environmental problems of (1) poor size and species selectivity, and (2) high fuel intensities.

The main concern is that, because of their small meshes and use in areas characterised by large abundances of small organisms, prawn trawls often catch non-target individuals (especially fish). Over the past two decades, this issue has been partially addressed via the installation of bycatch reduction devices (BRDs) into the posterior section (termed the 'codend') of trawls. Such modifications have dramatically improved selectivity, but none are 100% effective, and in some fisheries large numbers of unwanted organisms are still caught and discarded.

A second, more recent growing concern associated with prawn trawls is their relatively poor efficiency. Trawling produces a lot of drag, which requires substantial energy. Rising fuel costs, combined with concerns over carbon emissions, have led to an increasing impetus to reduce the inherent engineering deficits of this fishing method.

Conceivably both of the above environmental concerns associated with prawn trawling could be addressed via modifications to the anterior sections of trawls; primarily because this area ultimately (1) is responsible for much of the drag, and (2) regulates what is directed into the codend. However, one issue associated with testing often quite different anterior trawl sections is the potential for a confounding effect of relative horizontal trawl opening (termed "spread ratio" and defined as the headline length ÷ wing-end spread) on efficiency. No scientific work has been done to determine the importance of spread ratio on prawn-trawl performance.

We sought to address this shortfall here. Two identical beam-and-sled assemblies were configured to allow two identical trawls (7.35 m headlines) to be adjusted to spread ratios of 0.5, 0.6, 0.7 and 0.8, which were deployed behind a twin-rigged trawler in Lake Woolooweyah and towed across the same depth, current, towing speed and duration. Each spread ratio was tested during 30 tows.

The results showed that increasing spread ratio significantly increased drag (by up to 16%), without affecting absolute catches. However, when standardized to per ha trawled, significantly fewer targeted school prawns (biased towards larger individuals) and total bycatch by weight were retained in the wider-spread trawls. The catch reductions with increasing spread ratio were thought to reflect either: (1) slightly reduced ground gear contact and headline heights offsetting the greater swept areas; or perhaps more likely (2) steeper wing angles which increased the probability of mesh encounters for school prawns and were less efficient for herding fish. Based on this study, we conclude that future research comparing modified trawls should focus on maintaining similar spread ratios to minimise confounding effects.

**Configuring the mesh size, body taper and wing area of penaeid trawls to reduce environmental impacts**

*Lay summary*

Prawn trawling occurs throughout inshore waters of many tropical and temperate countries, and is an important source of income for many coastal communities. More than 100 species are targeted using a variety of trawl designs and methods of operation. While there are fishery-specific management concerns, virtually all prawn fisheries are characterized by the same two broad environmental issues.

The main concern is that, because of their small meshes and use in areas characterised by large abundances of small organisms, prawn trawls often catch non-target individuals (especially fish), termed 'bycatch'. Over the past two decades, this issue has been partially addressed via the installation of bycatch reduction devices (BRDs) into the posterior section (termed the 'codend') of trawls. Such modifications have dramatically improved selectivity, but none are 100% effective, and in some fisheries, large numbers of unwanted organisms are still caught and discarded.

The second, more recent growing concern associated with prawn trawls is their relatively poor efficiency. Trawling produces a lot of drag, which requires substantial energy. Rising fuel costs have led to an increasing impetus to reduce the inherent engineering deficits of this fishing method.

Conceivably, the above environmental concerns associated with prawn trawling could be concurrently addressed via modifications to the anterior sections of trawls; primarily because this area ultimately (1) is responsible for much of the drag, and (2) regulates what is directed into the codend. However, very little relevant research has been done. The aim of this study was to help address this shortfall, by assessing the importance of mesh size, trawl side taper (and therefore the total length) and wing depth (and therefore the amount of netting) in a common design of trawl body. The work was done in Lake Wooloweyah and the Clarence River, but the results have implications for other local and international prawn-trawl fisheries.

Five trawls were tested. The first trawl was made from 41-mm mesh (18 ply twine) and represented conventional designs (termed the '41 1N3B deep-wing'), while the remaining four trawls were all made from 32-mm mesh (12 ply) and differed only in their side tapers (1N3B‒~28° to the tow direction vs 1N5B‒~35°), and wing depths ('deep'–97 T vs 'shallow'–60 T). All trawls had 'Nordmøre-grid' BRDs installed, and each was deployed 38 times.

There were incremental drag reductions (and therefore fuel savings – by up to 18 and 12% per hour and hectare trawled) associated with reducing twine area (via either of the assessed modifications), and subsequently reducing otter-board area. Side taper and wing depth had interactive and varied effects on bycatch reduction, but compared to the conventional 41 1N3B deep-wing trawl, the 32 1N5B shallow-wing trawl (i.e. the design with the lowest twine area) caught significantly less unwanted fish (by up to 57%); which was explained by the shorter trawl allowing more individuals to swim forward and escape, either from the mouth of the trawl or via the Nordmøre-grid. In most cases, all small-meshed trawls also caught more school prawns (including both small and commercial-sized individuals) than the conventional 41-mm trawl.

The results observed here have implications for on-going research. Clearly, determining the most appropriate mesh size and ideally ensuring consistent openings throughout the trawl is an important precursor to other modifications. We showed that it is possible to reduce mesh size, but improve species selection through other changes, presumably because mesh openings mostly determined the selectivity of the targeted school prawns, whereas fish were more affected by changes in trawl geometry. Based on the mean sizes of school prawns retained, the 32-mm mesh we examined is too small. However, it should be possible to increase mesh size slightly to somewhere less than 41-mm, while still using a steep body taper to reduce fish bycatch, and with the least amount of twine area to minimise otter-board area and drag. These results support a philosophy of first optimising mesh size as a precursor to other anterior changes in other prawn-trawl fisheries.

**Comparing and modifying penaeid beam- and otter-trawls to improve ecological efficiencies**

*Lay summary*

Prawns are an important seafood throughout Australia, with 13 key species targeted using a variety of fishing methods. The gears used vary according to the location and species, with some estuarine fisheries involving stationary stow (termed 'pocket') and trap (termed 'running') nets and actively towed seines, hauls and beam and otter trawls. By comparison, coastal and offshore fisheries are limited to otter trawling and account for most of the total landed catches.

Irrespective of the method, most gears used to target prawns also catch at least some unwanted species (termed 'bycatch'). This is especially the case for beam and otter trawls, which have an additional disadvantage of being quite fuel intensive (i.e. high drag). Ongoing recognition of these issues has resulted in several recent studies aimed at assessing simple, yet holistic modifications to trawling systems to improve their environmental efficiencies. Even basic changes to the way trawls are spread and their design have been shown to significantly reduce unwanted catches and also drag.

This study aimed to contribute towards the above momentum, by comparing beam and otter trawls and also assessing simple modifications with these configurations. The configurations tested included traditional otter boards attached (1) with and (2) without so-called 'sweep wires' (3.15-m wires between the otter boards and trawl) to a 7.35-m headline trawl, and a beam rigged without sweeps to a larger 9.19-m trawl and (3) with and (4) without a horizontal wire and plastic streamers across the mouth (to stimulate an escape response in fish and direct them away from the trawl). These four trawling configurations were each towed 36 times behind a double-rigged vessel in Lake Wooloweyah.

The results showed that despite their greater total surface areas (7.5 vs 6.0 $m^2$), both beam-trawl configurations had significantly lower drags than the otter trawls (by up to 30%). Within-system drag was not affected by the modifications, although removing the sweeps wires from the otter trawl significantly reduced the horizontal opening (termed 'wing-end spread'). When catches were standardized to per ha trawled, the otter trawl with sweep wires retained significantly (1.3 to 2.4 times) more school prawns, *Metapenaeus macleayi*, than the other three configurations.

The relative fuel consumption rate (i.e. the L required to catch 1 kg of school prawns) revealed that the otter trawl with the sweep wires and the beam trawl with a horizontal wire were the most (0.990 L per kg) and least (1.320 L per kg) efficient, respectively. Within systems, removing the sweep wires from the otter trawls or adding a horizontal wire to the beam trawls significantly reduced the unwanted catches of one key fish species (southern herring, *Herklotsichthys castelnaui*) by 41 and 48%, contributing toward reductions in total bycatch of 41 and 20%.

Although still preliminary, the results illustrate the utility of simple refinements to existing prawn-trawling systems for independently and concurrently addressing key environmental issues. Future research is required to progress some of the concepts identified here, including the option for using beams instead of otter boards in some fisheries to not only reduce the amount of bycatch, but also the fuel used, or simply adding a horizontal wire to the mouth of otter trawls to reduce unwanted catches. Ultimately such work should contribute towards the ongoing viability of prawn trawling, not only in NSW but also nationally.

**Engineering and catching efficiencies of three conventional penaeid-trawl otter boards and the new 'batwing' design**

*Lay summary*

Prawns are targeted throughout the world's tropical and temperate regions; mostly using small fishing vessels (<25 m) towing multi-net trawl systems that are laterally spread by paired hydro vanes, called 'otter boards'. While there is considerable variability among otter-board designs, all encompass a substantial proportion of the entire trawl-system weight (to ensure sufficient seabed contact) and are orientated at an angle to the tow direction (termed the angle of attack – AOA). The AOA means that otter boards create substantial drag; hypothesised to account for >30−40% of the total system.

The strong contribution of otter boards to drag means that subtle variations and refinements to designs have the potential to improve overall trawl efficiencies, and ultimately the quantity of fuel required by prawn trawlers. Despite this, and while substantial theoretical work has been done, few studies have compared the relative engineering and catching performances of existing prawn-trawl otter boards, or subtle refinements, during conventional fishing.

This study contributes towards the limited information by describing three experiments to compare a novel, hydrodynamic otter board termed the 'batwing' (comprising a sled-and-sail assembly, configured to operate at 20$^{o}$ AOA, and with minimal bottom contact) against up to three conventional designs (termed the 'flat-rectangular'; 'kilfoil' and 'cambered' otter boards) with AOAs between ~30 and 40$^{o}$.

Using paired trawls (7.35-m headlines), the batwing otter boards were first tested against all other designs (30-min deployments) and then just the flat-rectangular design (50-min deployments). In the third experiment, the batwing and flat-rectangular otter boards were configured without trawls and towed to facilitate estimates of their 'partitioned' drag. Compared to the conventional otter boards, the batwing had up to ~86% less bottom contact and 18% less drag.

In terms of catches, the batwing otter board caught significantly fewer standardized weights of the targeted school prawns in experiment 1, but this was attributed to some confounding effects of rigging which were subsequently addressed in experiment 2. Among the conventional otter boards, the cambered design caught up to 13% more school prawns, attributed to its greater solid profile. None of the otter boards affected the catches of unwanted fish.

The results reaffirm that because otter boards contribute towards a large proportion of total system drag, their appropriate configuration is essential to maximise the efficiency of prawn trawls. This requirement will become ever more important as fuel costs rise, and concerns over habitat impacts of trawling increase.

**Traditional *vs* novel ground gears: maximising the environmental performance of penaeid trawls**

*Lay summary*

Prawns represent an important fisheries resource around Australia, with more than 13 species targeted in 13 separately managed fisheries, and by vessels towing either a single trawl, or two, three or four trawls in parallel. Irrespective of their configuration, all trawls are fished on the seabed and rely on sufficient substratum contact to stimulate prawns into the path of the trawl. Such contact is achieved using weighted 'ground gear' suspended from the bottom leading panel of the trawls, and comprising ropes with leads, or more commonly, various grades of chain link.

Despite accounting for most of the bottom contact and a considerable proportion of the overall weight of prawn trawls, the ground gear is one of the least studied components in terms of their effects on catches, engineering efficiency and habitat impacts. Many existing ground-gear configurations simply are the result of trial and error by fishers. Ideally there would be more quantitative information available to dictate the choice of particular designs.

Given the above, the aim of this study was to quantify the performances of three conventional ground gears for small estuarine prawn trawls, comprising either 6-mm (4.5 and 3.80 kg in air and water), 8-mm (8.42 and 6.88 kg) or 10-mm (13.07 and 11.20 kg) stainless-steel linked chain. A fourth ground gear was a novel design termed the 'soft-brush' (15.90 and 6.94 kg) and had a buoyed line with vertically suspended 4-mm link chain (giving 65% less linear bottom contact that the other configurations).

The four ground gears were tested beneath trawls attached to a purpose-built beam trawl during 24 deployments, with data recorded on their drag, and the catches in the trawls. The 6-, 8-, and 10-mm chains and soft-brush configuration produced predicted mean drags of 24, 30, 38 and 31 kg respectively, which represented 15, 18, 22 and 18% of the total system drag.

There were no significant differences in catches of the targeted school prawns in the trawls rigged among the different configurations, but the predicted means were up to 16% lower in the trawls with the 6-mm ground gear. The only species significantly affected by ground gear was small (5.0−8.5 cm total length) forktail catfish with the 6-mm catching up to 45% fewer than the 10-mm and soft brush ground gears; a result attributed to greater surface areas, and especially for the latter.

The performance of the soft-brush ground gear might be improved by reducing the surface area (and therefore drag), while still maintaining target catches and with minimal bottom contact. The importance of such advancements will become more relevant as fuel prices rise and concerns over habitat damage (and/or the fate of organisms escaping under the trawl) increase.

**Increasing lateral mesh openings in penaeid-trawl bodies to improve selection**

*Lay summary*

Prawn trawls are used along the coasts and throughout the estuaries of >25 countries worldwide. While each prawn-trawl fishery has its own specific management concerns, owing to the very small mesh sizes used, all fisheries are characterised by two broad, common environmental issues: (i) poor energy efficiencies (i.e. large amounts of fuel are required); and (ii) the capture and subsequent discarding of unwanted organisms, including individuals of the targeted prawns that are too small for sale.

Over the past decades, substantial efforts have been directed towards improving the environmental efficiencies of prawn trawls, and especially their species and size selection. Various retrospectively fitted modifications (including so-called 'bycatch reduction devices') have been developed and legislated. These modifications typically have been located in the codends of trawls (where the catch accumulates); mainly because this is where most selection is deemed to occur. While some of these modifications have dramatically improved selection, very few (if any) have addressed the first issue above of poor energy efficiencies.

More recent research has shown that simply changing the front sections of prawn trawls can improve both their efficiency and selection. In particular, first attempting to closely match the mesh size to the sizes of the targeted species, and then reducing the twine area and ensuring that the meshes are sufficiently open to allow unwanted organisms to escape can have considerable benefits.

In this study, we sought to follow the above logic for prawn trawls used in the Clarence River. Earlier work suggested that the existing legislated mesh size of 40-mm in the trawl body in this fishery might be slightly large for the targeted sizes of school prawns (typically 15−25 mm carapace length−CL). Consequently we constructed four smaller mesh trawls (made from 35-mm mesh) with considerably less twine area, which was achieved by steepening the side taper (from 1N3B to 1N5B or ~28 to 35$^{o}$), reducing the wing height, and ultimately the overall trawl length (by >30%).

The four small-meshed trawls differed in the amount of netting hung across their frame lines (termed the hanging ratio and defined as the stretched length of a hanging line or operating opening of a mesh panel divided by the stretched length of the mesh panel) and in the orientation of netting in the wing panels. Specifically, two trawls had frame-line hanging ratios of 0.550 (termed ‘loose’) and either diamond- or square-mesh (35-mm mesh hung on the bar) wings. The other two trawls had frame-line hanging ratios of 0.707 (‘tight’) and also either diamond- or square-mesh wings.

Compared to a 41-mm mesh conventional trawl, all of four smaller-meshed designs (comprising either loose or tight hanging ratios and with diamond- or square-mesh wings) caught the same amounts of commercial-sized school prawns, but had significantly lower drag (by 9−12%) and required less fuel (up 4−12%). Some of the small-meshed trawls also caught fewer unwanted fish—attributed to the steeper side panels allowing individuals to swim forward and escape.

In terms of the catches of unwanted, small school prawns (~<15 mm CL), the small diamond-mesh wing trawls caught more than the conventional trawl, although there was a reduction associated with increasing the hanging ratio. However, changing the mesh orientation was extremely effective, with both square-wing trawls retaining considerably fewer small school prawns than the two small-meshed, diamond-wing trawls (by up to 72%) and the conventional trawl (>50%).

The results support the concept of inserting square-mesh wings into prawn trawls as a means for improving their size selectivity, but ideally, this would be done for trawls with the most appropriate body mesh size. For the Clarence River, it is clear that the existing 40-mm mesh is not optimal for maximising size selection and fuel efficiency, but it is also clear that any reduction in mesh size would require other trawl parameters to be regulated and, in addition to wing-mesh orientation, perhaps the side taper (and body length) and frame-line hanging ratio.

**Influence of diel period and diurnal cloud cover on the species selection of short and long penaeid trawls**

*Lay summary*

Prawn-trawl fisheries are economically important for several developed and numerous developing countries, with more than 100 species targeted. While many fisheries are quite sustainable in terms of the targeted prawns, they often also catch and discard large quantities of unwanted organisms; the mortalities of which historically have raised substantial ecological concerns.

The simplest way of improving prawn-trawl selectivity is to install physical ‘bycatch reduction devices’ (BRDs) in the codends (the bag where the catch accumulates). Such modifications can reduce bycatches by more than 50%, and with no impacts on catches of the targeted prawns.

Bycatch reduction devices have been introduced in many prawn-trawl fisheries around the world and with varying degrees of success. However, one re-occurring limiting factor associated with BRDs is that they provide few immediate perceived benefits to the fisher, and can often represent addition work (in terms of their construction, maintenance and deployment). This means that in some fisheries, there has been resistance to adopt recommended BRDs.

Bycatch reduction devices are not the only modification to prawn trawls that can improve selectivity. Other changes can be made to the actual trawl body, including simply shortening it by increasing the side taper. Doing so increases the angle of netting and can open more meshes, providing improved opportunities for small fish to escape. An added benefit of such a modification is a reduction in twine area and therefore drag; which means shorter trawls required less fuel to tow. This latter benefit might help to facilitate the adoption of such modifications among fisheries.

While the engineering benefits of short trawls are clear, the actual mechanisms by which they help to reduce fish catches are less so. All of the work done to date has involved trawling during the day, and the potential exists for a visual response by some fish that contributes toward their escape. The aim of this study was to investigate this relationship by simultaneously testing a 'long' trawl with a conventional body taper against a 'short' trawl that had a steeper taper (by $7^{o}$ and 29% less length) during the night, and in daylight with variable cloud cover (categorized as <50 and >50%).

The work was done in Lake Wooloweyah, NSW over four nights and six days (total of 44 paired deployments). Catches were dominated by the targeted school prawns and seven species of fish. Only two fish (southern herring and Australian anchovy) along with the school prawns were significantly affected by trawl taper, with all retained in lower numbers by the short trawl.

For school prawns and Australian anchovy, their catch reductions remained consistent irrespective of night or day and daylight cloud cover, and were attributed to simple mechanical sieving through the steeper, more open meshes. But southern herring (mostly smaller individuals) only escaped from the short trawl during the daylight deployments and with <50% cloud cover; possibly through anterior meshes in response to more available ambient light.

The results highlight the importance of environmental parameters for affecting the selectivity of prawn trawls, and have implications for their ongoing refinement. Specifically, it might be possible to use contrasting netting panels or even artificially illuminate key areas of trawls to promote the escape of some fish during the night, or on cloudy days. Such ongoing research into ways that improve the selection of short trawls is warranted; especially considering the clear associated engineering benefits. The latter ultimately could help to promote the voluntary adoption of more selective trawling systems.

**A 'simple anterior fish excluder' (SAFE) for mitigating penaeid-trawl bycatch**

*Lay summary*

Prawn trawls are funnel-shaped nets towed along the seabed and typically spread by either hydro vanes (otter boards) or a rigid beam. All prawn trawls have relatively small mesh sizes and most are used in areas with diverse assemblages of small organisms. These characteristics mean that in addition to the targeted prawns, trawls often catch unwanted organisms (termed 'bycatch') which are discarded, sometimes dead.

One of the simplest ways of reducing unwanted bycatch from prawn trawls is to install physical modifications in the codend (where the catch is directed and accumulates), designed to separate species based on either their differences in behaviour, or size. Such so-called 'bycatch reduction devices' (BRDs) can reduce unwanted catches by >50%— often with minimal impacts on the targeted prawns. Providing most of the escaping organisms survive, BRDs can have positive benefits for stocks of interacting species.

Because codends are quite uniform among trawl fisheries, generic BRDs have been designed, implemented and legislated across fleets around the world. The widespread use of such devices is positive, although ideally unwanted species should not enter, nor interact with trawls in the first place. One method by which this could be progressed is to design BRDs that function at the front of the trawl. However, the utility of such modifications has not been comprehensively assessed; mainly because of the difficulty in developing generic solutions for a plethora of trawl designs and their configurations.

In this study we sought to contribute towards addressing the lack of information concerning BRDs located in the anterior trawl by designing and testing various modifications termed 'simple anterior fish excluders' (SAFEs), using a trawler fishing in Lake Wooloweyah, NSW. The SAFEs comprised flexible panels located between the spreading mechanisms (beam or otter boards) and across the mouth of trawls (all of which had the same BRD in the codend), and were designed to evoke an escape response in fish.

Initially, three SAFEs (a single wire without, and with small and large plastic panels) were secured to paired beam trawls and deployed against trawls with no SAFE. All SAFEs maintained the targeted catches of school prawns, while the large plastic SAFE significantly reduced the number of total bycatch by 47% and the numbers of tailor, mullet and southern herring (by 43−58%).

A redesigned SAFE (termed the 'continuous plastic') was subsequently tested on trawls spread by otter boards and significantly reduced total bycatch by 28% and the numbers of tailor and southern herring; both by up to 42%. The continuous-plastic SAFE also significantly reduced school prawns catches by ~7%, but this was explained by the greater drag causing ~5% less spread at the trawl opening, and could be simply negated through otter-board refinement.

Further work is required to refine the tested SAFEs, and to understand more clearly the factors contributing towards the escape of the key species. Nevertheless, the results support the concept of locating additional BRDs at the trawl mouth to incrementally improve selectivity. Owing to their simplicity, the SAFEs have the potential to be adapted to a range of trawl designs and configurations.

**Modifying otter boards to reduce bottom contact: effects on catches and efficiencies of triple-rigged penaeid trawls**

*Lay summary*

Prawn fisheries occur throughout the tropical and temperate oceans of the world, and mostly involve small vessels (8−25 m) towing multiple trawls (double-, triple and quad-rigs) that are spread on the seabed by hydro vanes (termed 'otter boards') orientated at between 35 and 40$^o$ (called the angle of attack—AOA) to the direction of towing. While there are a plethora of trawl designs and configurations, because of their large AOA, otter boards are known to consistently comprise a sustainable component of overall system drags, and are by far the heaviest individual component. These characteristics mean that in some fisheries there are concerns over possible habitat impacts, and in nearly all fisheries, issues regarding poor inefficiencies (i.e. excessive fuel use).

In recent years, there has been an increasing focus towards attempting to modify prawn-trawling systems, and especially otter boards, to reduce their environmental inefficiencies. One recent modification is the so-called 'batwing' otter board which comprises a unique sled-and-sail assembly, and is configured to operate at a 20$^o$ AOA, while minimising bottom contact by up to 90%. Recent tests with the batwing otter board and double-rigged trawls in the Clarence River (an important prawn fishery in NSW, Australia) also showed that this design reduced drag by 18% compared to trawls spread by conventional otter boards.

In addition to the batwing, there are subtle modifications to existing conventional otter boards that could reduce their habitat impacts and/or improve environmental efficiencies. One novel modification involves simply restricting AOA during fishing by using a pre-determined length of restraining line between otter boards. Conceptually, such a configuration should work, because while some otter boards require a large AOA to ensure stability during deployment, once on the bottom, the AOA can be substantially reduced.

Despite the above, apart from the study in NSW estuaries (and other theoretical flume tank studies), there has been very little work to investigate the batwing and other subtle modifications to existing prawn-trawl otter boards. The lack of data justified the present study to investigate the utility of the batwing and restraining conventional otter boards on a NSW oceanic prawn-trawler, towing triple-rigged trawls.

Over a total of 45 deployments, compared to conventionally rigged flat-rectangular otter boards (~40$^o$ AOA), both modifications reduced bottom contact by ~40 and 88% respectively. For the batwing, these reductions corresponded to 8 ha less bottom contact by the heavy otter boards over a night's fishing−which is quite a substantial area. Neither modification affected the standardised catches (per ha) of the targeted eastern king prawns nor the required fuel rate (L $h^{-1}$) or intensity (L $ha^{-1}$).

However, the trawls with the restraining line caught significantly fewer total unwanted bycatch (mostly small fish by up to 30%; possibly as a result of visual stimuli herding individuals away), while trawls spread by both modifications caught significantly more individuals of three benthic species (two of which were retained as 'by-product'). Although speculative, the latter result was hypothesised to occur via an improved transition between otter-board and wing-end AOA, and subsequent herding.

We conclude that while further work is required to refine the modified otter boards to reduce their drag when used with triple-rigged trawls, both represent simple alternatives for fisheries where there are concerns over the benthic impacts of trawling. Further, the restrained configuration warrants further testing for its utility in further reducing bycatch. Such work is likely to remain a priority for prawn-trawl fisheries worldwide.

**Hydrodynamic evaluation of a simple sail used in an innovative prawn-trawl otter board.**

*Lay summary*

Prawns are an important fisheries resource throughout the world's tropical and temperate regions. More than 100 species are targeted; mostly by small fishing vessels (<25 m) towing multi-trawl systems that are laterally spread by paired hydro vanes, called 'otter boards'. Otter-board designs vary considerably, but all encompass a substantial proportion of the entire trawl-system weight (to ensure sufficient seabed contact) and are orientated at an angle to the tow direction (termed the angle of attack–AOA). These characteristics mean that otter boards create substantial drag (e.g. at least 30% of the total system).

The contribution of otter boards to drag means that subtle variations and refinements to designs can dramatically improve overall trawl efficiencies, and ultimately the quantity of fuel required by prawn trawlers. A recent Australian innovation is the 'batwing' otter board; a novel design that spread trawls with substantially less towing resistance and with up to 90% less bottom contact. The latter is important because it could translate to fewer habitat impacts.

A key design feature of the batwing is the use of a sail instead of a flat plate, as the hydrodynamic foil. The superior drag and benthic performance of the batwing is achieved by (1) a constant AOA of ~20° and (2) having the heavy sea floor-contact shoe in line with the direction of towing. Preliminary trails with the batwing suggest 5−18% fuel savings, with no significant effects on catches of the targeted prawns. While such results are positive, design refinements need to continue; a prerequisite of which is to comprehensively understand how subtle adjustments to engineering parameters affect performance.

Considering the above, this study sought to provide a better understanding of the batwing's engineering performance by investigating the effects of varying the twist and camber of the sail to identify optimal settings for maximum spreading efficiency and stability. Loads in six degrees of freedom were measured at various AOAs between 0 and 40° in a flume tank at a constant flow velocity, and with five combinations of twist and camber.

The results showed that for the studied sail, the design AOA (20°) provides a suitable compromise between greater efficiency (occurring at lower AOAs) and greater effectiveness (occurring at higher AOAs). At optimum settings (20°, medium camber and twist), a lift-to-drag ratio >3 was achieved, which is about three times better than that of contemporary prawn-trawling otter boards, and should consistently provide drag reductions of up to 20%.

We conclude that further improvements to the batwing might be realised by evaluating other sail designs and sizes, including multi-foil configurations. Ultimately, such pro-active research will be important to ensure prawn trawling remains viable into the 21st century.

**The effects of twist and camber effects on the performance of simple hydro-sails used with an innovative penaeid-trawling otter board**

*Lay summary*

Over the past few years, rising fuel prices have substantially increased the input costs of wild-seafood production, especially among mobile small-meshed fishing gears like prawn trawls used in developed countries such as Australia (where labour costs are high). In direct response, there has been growing emphasis on researching and developing more fuel-efficient trawling systems.

Among most trawling systems, one of the single greatest contributors to total drag (and therefore fuel use) is the pair(s) of hydro vanes (termed 'otter boards') used to open the nets. Otter boards typically are orientated at 30−40$^{o}$ (termed 'angle of attack'—AOA) so that their drag creates a useful force to both keep the trawls open and hold them on the bottom. Optimising the hydrodynamic performance of otter boards is one approach that can result in substantial fuel savings for trawlers.

A recent novel otter board designed to substantially reduce unwanted hydrodynamic drag is the batwing. This design concept provides a relatively low AOA (20$^{o}$) solution that incorporates a flexible sail with a higher aspect ratio than traditional otter boards, and a unique towing arrangement to spread trawls with substantially less seabed contact. Understanding the key design factors affecting the hydrodynamic performance of the batwing otter board is pivotal to its effective refinement and promotion among industries.

Considering the above, this study investigated the effects of two important sail-design parameters (twist and camber) on the performance of two simple sail designs (with different rake angles) for the batwing in a flume tank (laboratory). Force and torque measurements were recorded for various twist and camber combinations across AOAs between 0 and 40°.

The major findings were that (1) changing the mast rake angle from 30 to 45° reduced lift-to-drag (L/D) at the design AOA by 14%; (2) the stall angle increased for the higher-rake angle, despite the associated sail being the higher aspect ratio of the two; and irrespective of rake angle, (3) optimal twist and camber are required for high sail performance and stable operation. Under optimal configurations and at 20° AOA, both batwing sails provided a L/D ratio of ~3, which is ~3 times greater than that for contemporary otter boards. During conventional trawling conditions, such results would manifest as drag (and fuel) reductions of up to 20%.

While the results are very positive, we conclude that further improvements to the batwing might be realised by progressing evaluations in the field and flume-tank testing other sail designs and sizes, including multi-foil configurations. Ultimately, such pro-active research will be important to ensure Australian prawn trawling remains viable into the 21$^{st}$ century.

**Relative benthic disturbances of conventional and novel otter boards**

*Lay summary*

Benthic trawling is the world's most common mobile fishing method and is used to target a plethora of fish, crustaceans and cephalopods. While there is huge variability in the design of benthic trawls, most are towed either individually or in pairs across the seabed, and held open by water pressure on hydro-vanes (so-called 'otter boards').

Otter boards function by providing a useful horizontal force through their angle of attack (AOA; ~20−40$^{o}$), but also need to be sufficiently heavy to help keep the trawl(s) on the seabed. In some trawl fisheries, the latter characteristic has raised concerns over perceived habitat impacts. While there are very few data, the possibility of impacts has generated attempts at mitigating or alleviating bottom contact, and typically via lifting the otter board off the seabed or minimising the AOA (and therefore the otter-board base-plate contact). An added advantage of minimising AOA is a reduction in drag and therefore improved efficiencies.

One novel otter board that is designed to minimise bottom contact, while still providing sufficient spreading force, is the batwing. This design comprises a sled aligned with the direction of tow, and an offset sail that lightly touches the seabed. Preliminary data suggest that the batwing can reduce drag and fuel usage by up to 18%. No data are available describing any concomitant reduction in habitat impacts.

This study aimed to address the above shortfall by comparing relative differences in material and catches displaced by the batwing and a conventional otter board. Pairs of each otter board were suspended beneath a purpose-built rig comprising a beam and posterior, semi-pelagic collection net and repeatedly deployed for ten minutes across established trawl grounds in Lake Wooloweyah, NSW.

Compared to the conventional otter-board pair, the batwings displaced significantly fewer empty shells (by 89%) and school prawns (by up to 78%) at rates that were closely correlated to the reduction in base-plate bottom contact between designs (87%). Further, there were proportionally fewer damaged shells by the batwing; attributed to their displacement away from the otter-board's surface area. Other debris (lighter pieces of wood) and benthic fish (bridled gobies) were not as greatly mobilised (e.g. reduced by 50 and 25%); possibly owing to their orientation on, or slightly off, the bottom, and a more common influence of hydrodynamic pressure by the otter-board surface areas.

Although the consequences of reducing otter-board bottom contact largely remain unknown, designs with low AOAs like the batwing may represent a beneficial option for those fisheries where trawling is perceived as being hazardous to sensitive habitats. Future research warrants as assessment of such reductions and also the potential for fuel savings. Holistically addressing both of these issues via simple modifications seems a coherent approach to reduce the broad environmental impacts of benthic trawling.