Improving and promoting fish-trawl selectivity in the Commonwealth Trawl Sector and Great Australian Bight Trawl Sector of the Southern and Eastern Shark and Scalefish Fishery

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Executive summary

Concept

This project sought to produce the first-ever review of technical options for improving fish-trawl selectivity around the planet and then use this information to address a deficit in experimental work quantifying the utility of industry-developed and new selective-gear modifications in the Commonwealth Trawl Sector (CTS) and Great Australian Bight Trawl Sector (GABTS) of the Southern and Eastern Scalefish and Shark Fishery (SESSF). The work was completed during a four-year collaboration (from September 2020) between the New South Wales Department of Primary industries (NSW DPI), Fishwell Consulting, the Australian Fisheries Management Authority (AFMA), Commonwealth Scientific and Industry Research Organization (CSIRO), South East Trawl Fishing Industry Association (SETFIA) and the Great Australian Bight Industry Association (GABIA). Ultimately, by highlighting regional industry efforts and identifying and validating the benefits of new options to reduce one of the most controversial issues facing bottom trawling, the project contributes towards improving the social licence and economic return of trawl fisheries in the SESSF, and supports ongoing Australian research into technological solutions to ensure fishery sustainability.

Background

Fish-trawl fisheries are important throughout south-eastern and southern Australia with >20 species targeted and >100 other species considered by-product, providing ~>15 000 mt valued at >$50 million p.a. Most of these catches are taken in the CTS and GABTS which, like all other regional and global trawl fisheries, are characterized by often poorly selective conventional gear configurations. At some times and locations, large amounts of bycatch, including non-commercial species, juveniles of commercial species and, less frequently, some vulnerable species are caught and discarded by CTS and GABTS fish trawlers.

Thirty years ago, recognition of the wastage associated with the mortality of fish-trawl bycatch led to research in the CTS (and adjacent NSW state waters) assessing simple modifications to codends, initially involving larger mesh followed by bycatch reduction devices (BRDs), including square-mesh panels, to allow small unwanted fish to escape. Some of these modifications reduced bycatches and supported legislative changes in the SESSF by 2006. These changes, along with a reduction in fishing effort and spatial closures, have reduced unwanted fishing mortalities and with positive benefits to some stocks. Nevertheless, the drivers of discarding in quota-managed, multi-species fish trawl fisheries are complex, and because of the highly variable target and by-product species, large amounts of unwanted catches are still discarded.

In recent years, some CTS, GABTS and NSW inshore fish-trawl fishers have investigated simple modifications to gears (including changes to mesh sizes and orientations at strategic locations) to improve selection. These modifications require prioritization, evaluation and empirical testing and, where appropriate, their broader adoption should be encouraged. It is also well-established that over the past two decades, similar bycatch issues in overseas fish-trawl fisheries have led to various novel technical and operational changes for improving selectivity.

Considering the above, the aim of this four-year research project was to work with trawl fishers in the CTS and GABTS to prioritise, assess and then refine suggested technical modifications designed to reduce bycatches while maintaining target and by-product catches. In doing so, the project supports the wide-scale voluntary adoption and ongoing exploration of appropriate best-practice technologies that should not only cumulatively improve the harvesting of important Australian fish stocks, but also positively impact social expectations.

Objectives

The objectives of the project were to:

1. Review the available domestic and international literature and consult with a project stakeholder committee (comprising representatives of the CTS, GABTS, AFMA and the NSW Professional

Fishers' Association) to prioritise modifications to be formally assessed for their utility in minimising bycatch while maintaining target catches among trawls used in the CTS and GABTS.

2. Based on the outcomes of 1 above, assess the utility of existing and new modifications to trawls for minimising bycatch while maintaining target catches in the CTS and GABTS.

3. By providing strong economic incentives through improved efficiencies, and via applied extension activities, encourage the wide-scale voluntary adoption and ongoing exploration of appropriate best-practice technologies that cumulatively reduce bycatches while maintaining target catches in the CTS and GABTS.

Methods

The project was done in three phases. Phase 1 required two literature reviews: one that summarized Australian fish-trawl fisheries and the history of modifications to improve selectivity, with reference to the CTS and GABTS; and another that synthesised all previous international assessments of selective fish-trawl modifications as a basis for proposing a framework for future regional work. Following phase 1, manipulative experiments were done to address the second project objective of assessing the utility of existing industry-priority modified gears and/or practices (phase 2) and then new, alternative configurations (phase 3) in the CTS and GABTS. The benefits of changing selectivity were also assessed for some key species via stock modelling.

For the CTS, the first industry priority involved assessing different centre ground-gear disc diameters (4 in/100mm vs 7 in/170 mm vs 10 in/252 mm). We also investigated a variation of a square-mesh panel BRD among NSW inshore trawlers. In the GABTS, industry priorities were entirely directed towards conventionally used four-seam 'T90' (i.e. mesh turned 90^{o}) cylinders (94-mm mesh stretched mesh opening; SMO) with shortened lastridge ropes (i.e. along each seam) in the front 50% of the codend. There were perceptions about the utility of these alternative gears in both fisheries that included less bycatch with marginal reductions in target catches, and for the T90 codends in the GABTS, an improved quality of targeted Deepwater Flathead, *Platycephalus conatus*. A horizontal-separator panel and dual codends were also tested in a generic trawl to ascertain species-specific vertical preferences during progression from the aft body to the codend and to better understand behaviour with a view to improving trawl selectivity. This information was used to prioritize new modifications for testing in phase 3 (and beyond for future projects).

During phase 3 in the CTS, questions were asked concerning the utility of entire four-seam, shortened lastridge-roped T90 codends and factors affecting their performance, and a lower-headline trawl for improving size and/or species selectivity, respectively. Phase-3 research in the GABTS remained with four-seam, shortened-lastridge-rope T90 codends, and more specifically, larger mesh (increased by 10 mm to 105 mm SMO) to better match the morphology of Deepwater Flathead at their mean size of maturity (~40 cm total length; TL).

Through extensive consultation within all three phases and via detailed extension activities, the third project objective was addressed. Realization of these outcomes included encouraging the adoption of a modification developed during the project among NSW fish trawlers and further exploring ideas according to the proposed framework developed from the international review of the available literature.

Results

The national literature review summarized 11 fish-trawl fisheries around Australia, which encompassed 118 licenses, and with the CTS and GABTS collectively accounting for ~35%. Over the past 25 years, there have been seven projects aimed at modifying fish trawls in these (and adjacent NSW) fish-trawl fisheries, funded by the FRDC, NSW DPI and/or AFMA. The projects supported management changes for trawlers working in both NSW inshore waters and in the SESSF. Logbook data for the CTS and GABTs were neither consistently nor well recorded over time, but nevertheless showed variability in trawl configurations, including for codend mesh sizes (typically diamond-shaped at 90–100 mm SMO) and

BRDs—often comprising square-shaped or T90 meshes. Other differences include variable ground gear-disc diameters, which were thought to affect selection.

Internationally, 203 papers were found describing manipulative experiments assessing the selectivity of trawl modifications. Many studies focused on European fisheries and their key species, such as Haddock, *Melanogrammus aeglefinus* and Atlantic Cod, *Gadus morhua*. Only 3% of all relevant papers published in international journals described efforts to improve size and/or species selection in Australian fish trawls. Most of the Australian work done prior to the present project is limited to publication in internal reports (i.e. 'grey literature').

Nevertheless, the modifications tested in Australian fish-trawl fisheries have mirrored those overseas and all were categorized into four zones, with options chosen according to the known size and morphology of key species and their assumed behaviour and swimming capacity. Zone 1 includes spreading mechanisms (i.e. warps, otter boards, sweeps and bridles), among which there were limited assessed changes and with raised sweeps often showing the strongest effects (attributed to visual responses). Zone 2 comprises the headline, foot rope and ground gear, with lowered headlines, and raised foot ropes and/or ground gear often yielding selective benefits. Zone-3 modifications occur at the trawl wings and body and include larger-mesh openings and windows throughout. Zone-4 modifications encompass changes to the lengthener/extension and codend and were, by far, the most common (70% of efforts), with changes involving increasing and maintaining lateral-mesh openings via larger diamond mesh or smaller square or T90 meshes; either as window BRDs or entire cylindrical sections. The success or otherwise of various zone-specific modifications informed a general framework for assessing fish-trawl modifications and facilitated identifying options for testing in the CTS and GABTS during the project.

Reflecting international efforts, zone-4 modifications were a key focus during both phases of experimental work in the project. During phase 2, the industry-developed T90 anterior-codend cylinder for the GABTS was shown to not affect selectivity at all with discarding remaining very high (~67% and mostly due to excessive catches of Wide Stingaree, *Urolophus expansus*). But the 94-mm T90 codend did improve the skin quality of Deepwater Flathead. In phase 3, simply increasing the size and number of T90 meshes benefited fish selection in the GABTS, albeit requiring further refinement and with no possible effects on Wide Stingarees. The utility of increasing the number of T90 meshes and their position close to the end of the codend was further demonstrated during phase 3 for the CTS when targeting Tiger Flathead, *Platycephalus richardsoni* and this modification significantly increased commercial catches of Latchet, *Pterygotrigla polyommata* without affecting any other species. Notwithstanding this result, a slightly larger T90 mesh would be required to more effectively separate undersized Tiger Flathead (<28 cm TL) in the CTS.

Other zone-4 work revealed the need for improvements in the size selection of inshore Eastern School Whiting, *Sillago flindersi* trawls, but reiterated the utility of square-mesh window BRDs in the tops of codends for allowing small fish to escape because many rise up in front of the catch. Species-specific variability in the latter behaviour was identified during phase 3 in the horizontal-separator panel experiment, which also supported slightly lowering the headline of a conventional CTS trawl to maintain species selection for Tiger Flathead while reducing drag. The remaining work with changing the anterior trawl involved assessing the effects of ground-gear disc diameters during phase 2, but failed to detect any significant effects on catches, reiterating no need to mandate ground-gear dimensions across the studied areas in the CTS.

Implications

The project provides empirical data published in the international literature to describe the performance of some industry-developed modifications to the trawl bodies and codends of fish trawls in the CTS and GABTS and, in doing so, facilitates justification (or otherwise) for existing legislated options as well as prioritising future efforts to maintain target and by-product catches, while minimising unwanted catches. Modelling of changes to stock statuses associated with reducing fishing mortality supported progressing the types of gear refinements suggested. The longer-term implications of such outcomes are improved environmental viability and a robust base from which scientists and fishers in the CTS and GABTS can direct future efforts towards improving profitability and mitigating the environmental impacts associated with trawling.

Recommendations

Substantiated recommendations from the project are to:

- Maintain unregulated ground-gear disc diameters within the assessed range in the SESSF;
- Consider a minimum legal length (MLL) for Deepwater Flathead to facilitate adopting larger mesh sizes in the GABTS;
- Increase the minimum legal diamond-shaped mesh size in the GABTS by ~5–10 mm to reflect larger target species than in the CTS;
- Decrease the minimum T90-mesh size in BRDs (and/or codends) in the CTS by ~10–15 mm (single twine) to better match the small MLL (28 cm TL) of Tiger Flathead.
- If made of double twine, increase the minimum T90 and square mesh used in BRDs by at least 5 mm in the GABTS (given the current specifications are ineffective);
- Regulate twine diameter, proportional to mesh size throughout the SESSF;
- Address the poor selectivity of inshore (NSW) fish trawls for Eastern School Whiting via legislated changes to mesh size/shape in codends;
- Explore post-capture options to reduce discarding, by promoting markets for discarded commercial species (e.g. Latchets in the GABTS);
- Use information on species-specific variability on movements in trawls to explore options to reduce catches of stingarees and other elasmobranchs (which comprised ~1/3 of most catches);
- Encourage ongoing industry participation in solutions to ameliorate discarding; and
- Encourage funding agencies to specify the publication of fishing-gear technology results in international journals to maintain rigorous experimental designs, analyses and review.

Keywords

Anterior trawl modifications; Bycatch; Discards; Fish trawl; Multi-species; Selectivity; Square mesh; T45 mesh; T90 mesh

Introduction

Benthic fish trawling is among the oldest and most economically important fishing methods throughout temperate south-eastern and southern Australia, producing >15 000 mt valued at >$50 million p.a. (Tilzey and Rowling, 2001; Novaglio et al., 2018; van Putten et al., 2019). Most catches come from the Commonwealth Trawl Sector (CTS) and adjacent Great Australian Bight Trawl Sector (GABTS) of the Southern and Eastern Scalefish and Shark Fishery (SESSF) which is managed by the Australian Fisheries Management Authority (AFMA). These two separated trawl fisheries extend south from Sydney, New South Wales (NSW) around Tasmania to Kangaroo Island, South Australia (CTS), and then west to Cape Leeuwin, Western Australia (GABTS) and currently comprise ~30 and 3 active trawlers (from 36 and 11 licenses), respectively towing single-rigged fish trawls (headline lengths mostly between 30 and 45 m; Figure 1). In total, >20 and 100 species are either targeted or considered ‘by-product’, respectively, with 34 species/groups currently under quota (total allowable catches). However, Tiger Flathead, *Platycpehlus richardsoni* (the only species with a minimum legal size at 28 cm total length; TL), Blue Grenadier, *Macruronus novaezelandiae* and Pink Ling, *Genypterus blacodes* have consistently dominated targeted ‘market-fishing’ catches in the CTS on the self and upper slope, while Deepwater Flathead, *Platycephalus conatus*, Bight Redfish, *Centroberyx gerrardi* and Ocean Jacket, *Nelusetta ayraud* are key targets in the GABTS.

Like for all trawl fisheries around the world, in the CTS and GABTS none of the gear configurations used—which are similar to those used in other Australian trawl fisheries, including adjacent inshore NSW trawl fisheries—are entirely selective for the targeted species, and so unwanted organisms comprising >300 species and 40–60% of the total catches (including juveniles of the targets and by-product) are routinely discarded as bycatch (Kennelly, 1995; 2021; Liggins, 1996; Knuckey and Ashby, 2009). Although quite variable, the discard rates of CTS and GABTS vessels when targeting market fish are up to twice the global average for similar temperate fish-trawl fisheries (~30%) and more comparable to those for small-meshed, tropical penaeid trawls (~56%; Pérez Roda et al., 2019). High discard rates in the CTS and GABTS have maintained ongoing concerns over wastage and impacts to the stocks of key species (Kennelly, 1995; Liggins, 1996; Department of Agriculture and Water Resources, 2018; van Putten et al., 2019).

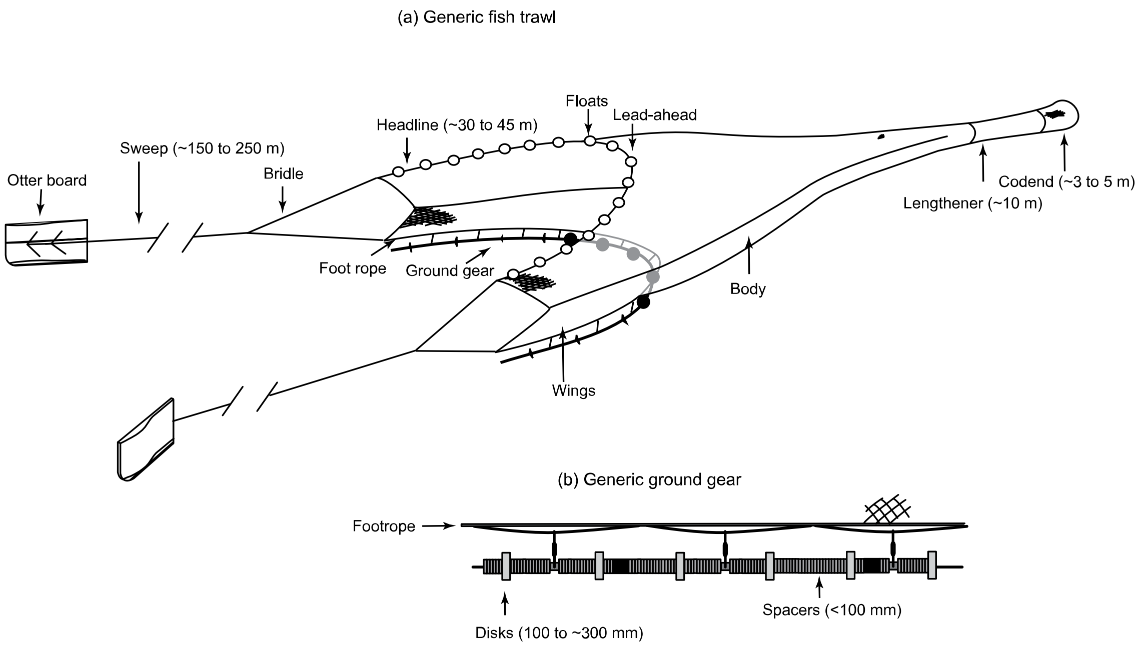

Figure 1. A generic (a) fish trawl, with the various components identified including (b) ground gear.

Thirty-years ago, cumulative recognition of the negative impacts of unwanted fishing mortalities associated with all fish-trawl fisheries off south-eastern Australia (and prior to the current jurisdictional management of SESSF trawl fisheries; Novaglio et al., 2018) justified initiating efforts at investigating simple, applied technical modifications to improve size selection (Broadhurst and Kennelly, 1995; Knuckey and Ashby, 2009). The tested modifications have been diverse, but mostly included slightly larger conventional diamond-mesh (termed 'T0') sizes in the trawl body and codend (from a minimum legal size of 90 mm stretched mesh opening; SMO) and reducing twine diameter, as well as bycatch reduction devices (BRDs) involving turning meshes 45° to create square openings ('T45' mesh) in codends (Figure 2). Many of these modifications were shown to reduce unwanted catches and led to some legislative refinements in 2006 (Knuckey et al., 2018). Additionally, following overseas efforts (Moderhak, 1997), preliminary research with turning panels of netting 90° ('T90' mesh; Figure 2) by Knuckey et al. (2008) supported subsequent regulation changes.

Currently, CTS and GABTS fishers must use:

1. a mesh size (SMO) in the wings and the net mouth ('shoulders', 'belly' and 'veranda' or wings) not less than 115 mm; and in the codend (Figures 1 and 2):

2. a mesh size of: a. at least 90-mm single twine mesh; or b. double twine mesh of at least 102-mm or greater; or c. at least 90-mm double twine mesh with one or more bycatch reduction devices.

And a bycatch reduction device needs to be constructed as follows:

1. a single large square mesh (of at least 90 mm) panel in the upper side of the codend (of minimum dimensions 15 bars × 20 bars); or

2. a single, large, rotated mesh (of at least 90 mm) panel (called a T90) in the upper side of the codend (of minimum dimensions 15 meshes × 18 meshes).

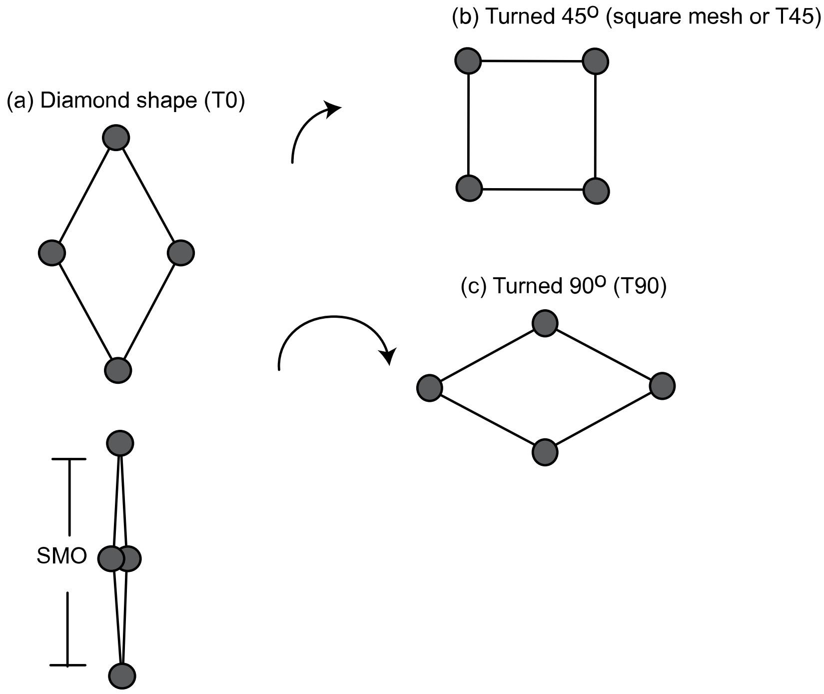

Figure 2. Meshes orientated in (a) a traditional diamond shape (termed 'T0') with stretched mesh opening (SMO) indicated and turned (b) 45° to make square-shaped mesh (termed 'T45' mesh) or (c) 90° to make 'T90' mesh.

Changes to CTS and GABTS fish-trawl configurations have had positive, fleet-wide effects on size and/or species selection, but because the fisheries are dynamic with variable target and by-product species sizes and shapes, at some times and locations large numbers of unwanted fish are still caught and discarded. As part of ongoing attempts at improving size or species selection, CTS and GABTS fishers have investigated modifications to gears that extend beyond changes to mesh sizes and orientations in panels at strategic locations, to include entire codend sections of T90 mesh comprising four seams and shortened so-called 'lastridge' ropes (made from Dynema®) designed to hold meshes open, or alternative trawl-body designs and configurations, including different ground gears. There are anecdotal reports of variable effectiveness among modifications for reducing bycatches, while maintaining target/by-product catches. Nevertheless, the performances of these industry-led modifications need to be formally assessed, and ideally as part of empirical experiments subjected to international standards of review and critique—which provide the strongest evidence to inform fisheries management and ultimately to support refinements, broader adoption, and eventual legislation (Gannon, 2001; Cvitanovic et al., 2015).

It is also well-established that over the past three decades, similar bycatch issues in overseas fish-trawl fisheries, and especially those in the North Atlantic Ocean, have led to many technical solutions that have improved size or species selectivity, and also refined empirical methods for prioritizing and investigating coherent options. Nevertheless, unlike modifications to penaeid trawls which have been extensively studied and reviewed (Broadhurst, 2000; McHugh et al., 2017), there has not been a formal review of the large body of published work describing the amelioration of bycatch via technical modifications to fish trawls. Collating and reviewing this work will support a framework for the future testing of selective modifications in relatively less studied fish-trawl fisheries like the CTS and GABTS, and indeed all other Australian fish-trawl fisheries.

More broadly, based on previous research with most active fishing gears, it is very clear that fishing-technology research to improve resource harvesting is a priority need for the future sustainability of all types of trawling in Australia (McHugh et al., 2017). The issue is quite poignant, considering that over the past 15 years, there has been a >40% reduction in the total number of trawlers around Australia, and lower profits among many remaining operators struggling to remain viable. Commensurate with decadal focuses on resolving environmental issues in Australian penaeid-trawl fisheries (some of which are among the world's most selective owing to modified gears; Kennelly, 2021), there is a need to increase efforts at identifying and/or developing innovative, high-priority technological modifications to fish trawls in the CTS and GABTS that mitigate sustainability issues while maintaining target catches at existing levels. Equally important, ratified designs need to be tested across fleets to encourage adoption and refinement as a precursor to eventual legislation. Ultimately, satisfying these needs will contribute towards improving the social licence and economic return of the CTS and GABTS, while helping to ensure their ongoing sustainability and address what remains one of the most controversial issues facing bottom trawling.

Objectives

The contracted objectives of the project were to:

1. Review the available domestic and international literature and consult with a project stakeholder committee (comprising representatives of the CTS, GABTS, AFMA and the NSW Professional Fishers' Association; PFA) to prioritise modifications to be formally assessed for their utility in minimising bycatch while maintaining target catches among trawls used in the CTS and GABTS.

2. Based on the outcomes of 1 above, assess the utility of existing and new modifications to trawls for minimising bycatch while maintaining target catches in the CTS and GABTS.

3. By providing strong economic incentives through improved efficiencies, and via applied extension activities, encourage the wide-scale voluntary adoption and ongoing exploration of appropriate best-practice technologies that cumulatively reduce bycatches while maintaining target catches in the CTS and GABTS.

Methods

The project was a four-year study involving three phases—each preceded by appropriate consultation among a project stakeholder committee comprising representatives of the CTS, GABTS, AFMA and the PFA (where relevant). During phase 1, face-to-face meetings were held with CTS and GABTS fishing-industry representatives to provide them with the project details. At these meetings, information was sought on existing trawl configurations and any industry-developed modifications used in the fisheries, including anecdotal data on their relative effectiveness. Doing so partially supported addressing the first project objective, involving a national review that summarized current Australian fish-trawl fisheries and then focused on the history of trawl selectivity and gear development in the CTS and GABTS (Appendices 3 and 14). Equally importantly, a review of the available international literature was also undertaken to propose a framework for future testing and assessing selective fish-trawl modifications in the CTS and GABTS (Appendices 4 and 15).

Following phase 1, manipulative experiments were done with chartered CTS and GABTS fishers to address the second project objective of assessing the utility of (1) existing priority modified gears and/or practices (phase 2) and then (2) new, alternative configurations (phase 3). Within phases 2 and 3, and via the detailed extension activities below, objective 3 was addressed, which included encouraging the adoption of a modification developed during the project (Appendix 18) and exploring generated ideas. Finally, some preliminary desk-top modelling was done to investigate examples of the likely changes to the stock statuses of three species representing divergent life-histories following hypothetical changes to gear selectivity (via the types of investigated modifications assessed in phases 2 and 3) that might be evoked in the future. Summaries of the relevant phase-specific methods are provided below, with greater detail in the various Appendices.

Phase 1: national and international reviews of the relevant literature

Both the national and international reviews sought to collate information describing all technical efforts to improve the size and/or species selectivity of fish trawls (and so reduce bycatch) via gear modifications, but the methods for each review followed different criteria. For the national review, only Australian studies, including those published as 'grey' literature (i.e. internal or agency reports) or in peer-reviewed scientific journals were collated. Relevant reports were collected using searches of completed FRDC, AFMA and state-funded projects and by contacting known project proponents and industry representatives. In some cases, the completed projects resulted in a scientific output that was published in an international journal, but in most cases, only grey literature was available describing efforts at improving the size and/or species selection of Australian fish trawls.

To achieve broader, critical consideration of the anonymously peer-reviewed science in the field, the international review was restricted to only those papers published in all listed scientific journals. Relevant works were acquired with reference to the 'preferred reporting items for systematic reviews and meta-analyses' (PRISMA) method (Liberati et al., 2009). To ensure inclusiveness, the starting point was ~150 scientific papers collected by the international-review authors over 30 years. From these papers, 22 common key words were collated and then used in combinations to search for additional papers (between 1988 and 2020) via the ISI Web of Science and Google Scholar. The papers were read, summarised and used to propose a framework for the future testing of modifications in less-studied fisheries, including the CTS and GABTS.

Phases 2 and 3: manipulative experiments to test modified gears and questions asked

Following completion of both reviews, all subsequent field experiments were designed based on identified knowledge gaps and with consultation among the project steering committee. Specific questions (hypotheses) were formulated, and then the appropriate experimental designs were developed and summarized (Table 1). These experimental-design summaries were included in requests for expressions of interest (EOIs) that were sent to all endorsement holders in the relevant fisheries, seeking vessel charters. All EOI applicants were evaluated following established protocols by Fishwell Consulting, prior to selection and contracting by NSW DPI.

The types of modified gears assessed varied, but a maximum of three (and usually only two) treatments were fished during each experiment (Table 1). During phase 2, the objective was to assess the utility of existing industry-tested options. For the CTS, the chosen treatments included variable centre ground-gear disc diameters (100 mm or 4 inch vs 170 mm or 7 inch vs 252 mm or 10 inch discs) that encompassed most (nearly 90%) of the fleet's characteristics (Appendix 5). As part of approved pilot work on an inshore NSW trawler we assessed a codend cover, and a variation of the square-mesh panel BRD (Table 1, Figures 3 and 4; Appendix 6). In the GABTS, industry priorities revolved around conventionally used four-seam T90 cylinders (94-mm SMO) with shortened lastridge ropes in the anterior codend—modified and adopted after earlier regional research (Knuckey et al., 2008) (Table 1, Figure 5a; Appendix 7). There were industry perceptions about the utility of these alternative gears in both fisheries that included less bycatch with marginal reductions in target catches and, for the T90 codends in the GABTS, an improved quality of the targeted Deepwater Flathead.

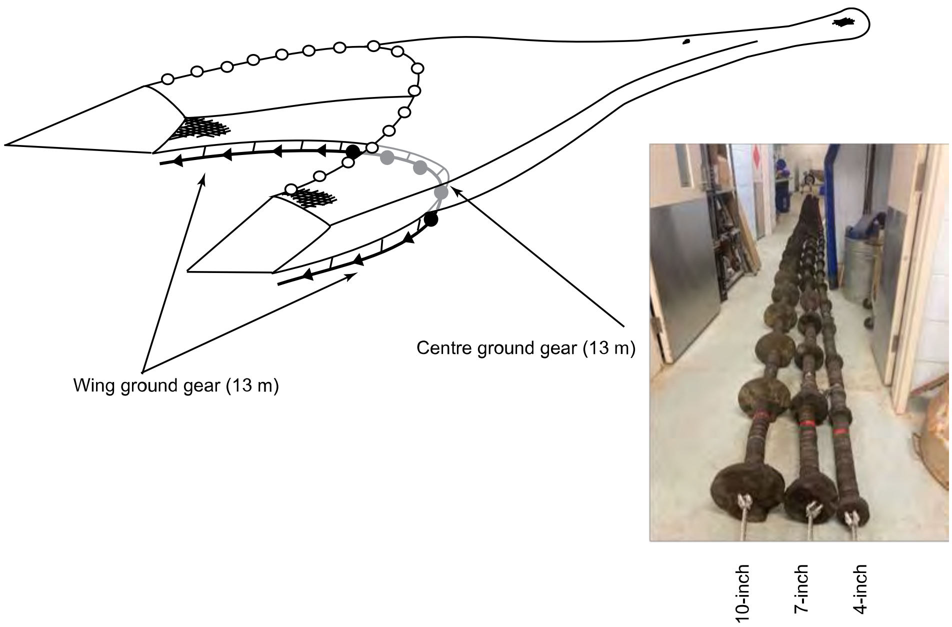

Figure 3. A trawl showing three 13-m centre ground gears comprising 100-mm (4 inch), 178-mm (7 inch) or 252-mm (10 inch) rubber discs that were alternated between two 13-m wing ground gears (with a maximum disc size of 4 inches).

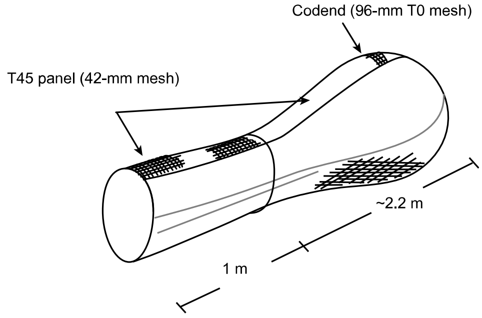

Figure 4. A conventional T0 codend with a T45 panel extending throughout the entire top ¼ and 1 m into the lengthener/extension.

(a) T90 and T0 codends

(b) Three T90 codends

Figure 5. Photos of (a) T90 anterior codend (with a T0 posterior section) and traditional T0 codend throughout (all made from 94 mm stretched mesh opening; SMO) and (b) three T90 codends with different mesh sizes (94 and 105 mm SMO) tested in the GABTS during phases 2 and 3, respectively. All T90 codends comprised four seams with shortened lastridge ropes (83% of stretched codend length) at each juncture.

We also sought to better understand fish behaviour in a generic fish trawl as a precursor to recommending new modifications to test during phase 3 (Appendix 8). This work involved fishing a trawl with a horizontal-separator panel and dual codends to ascertain species-specific vertical preferences during progression from the mid to aft trawl body (Table 1, Figure 6). Questions concerning fish movements helped to prioritize phase-3 modifications for testing in the CTS and beyond for future projects (Table 1).

During phase 3 in the CTS, questions were asked concerning the utility of entire four-seam, shortened-lastridge-roped T90 codends and factors affecting their performance, and a lowered headline height for improving size and/or species selectivity, respectively (Table 1, Figure 7; Appendix 9). Phase-3 research in the GABTS remained with four-seam, shortened-lastridge-rope T90 codends, and more specifically, larger mesh (increased by 10 mm to 105 mm SMO) to better match the morphology of the key target, Deepwater Flathead at their mean size at maturity (i.e. ~40 cm TL) (Figure 5b).

The project team proposed to expand work in the GABTS to include ground-gear modifications comprising tickler chains (in front of the trawl and designed to stimulate organisms upwards into the mouth) and horizontal separator panels into dual codends to separate very abundant elasmobranchs, and especially the Wide Stingaree, *Urolophus expansus*. However, there was no industry support for this work, and so the remining research efforts were refocused on the CTS.

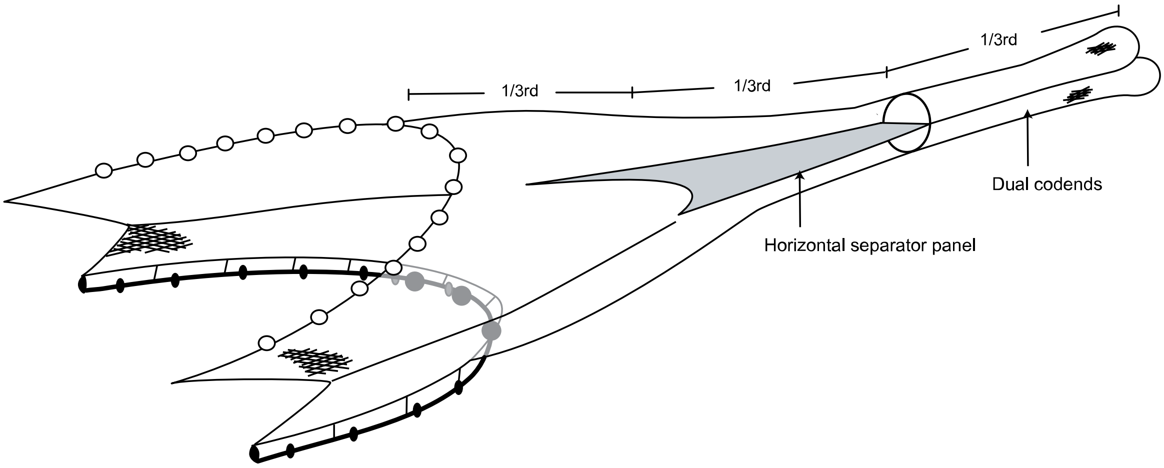

Figure 6. The horizontal separator panel leading to dual codends used to quantify species-specific differences in vertical distributions after entering a CTS trawl during phase 2.

Figure 7. Photos of narrow (left) and wide (middle) 71-mm (stretched mesh opening; SMO) four-seam T90 codends with shortened lastridge ropes (83% of codend length) and a traditional two-seam 91-mm SMO T0 codend (right) tested in the CTS during phase 3.

Table 1. **Summaries of the experiment phases (phase two was dedicated to existing modifications and phase three to alternative/new modifications), fishing locations, specific questions asked (i.e. hypotheses), treatments tested, total numbers of days and deployments of each treatment, and the appendix containing the relevant report. SMO, stretched mesh opening; CTS, Commonwealth Trawl Sector; GABTS, Great Australian Bight Trawl Sector; T0, diamond-shaped meshes; T45, meshes turned 45º (square-shaped); and T90, meshes turned 90º (see Figure 2 for details of the mesh shapes). All T90 codends comprised four seams with shortened lastridge ropes (83% of the stretched codend length) at each juncture and all mesh sizes are SMO.**

Phase	*Fishery and location*	*Questions asked?*	*Treatments*	*Total no. of days and deployments per treatment*	*Appendix*
Two	CTS, from Ulladulla	Does the disc diameter in the centre third of the ground gear affect the size or species selection of a generic trawl across inshore and offshore grounds?	Three ground-gear centre pieces (Figure 1): 100 mm (4 in.) vs 178 mm (7 in.) vs 252 mm (10 in.) alternately fished on a conventional 38-m two-seam trawl (Figure 3).	12 days with 12 deployments per ground gear.	5 and 17
Two	Inshore, NSW, Ulladulla	Does a modified T45 panel BRD improve eastern school whiting selectivity, and does a cover affect their escape?	A 47-mm SMO cover and two codends: the first was a conventional T0 design made from 96 mm SMO; and the second the same design, but with a panel of 42-mm T45 mesh throughout the top ¼ of the entire design (Figure 4).	Six nights and eight or nine deployments of each configuration.	6, 17 and 18
Two	GABTS, from Port Lincoln	Does an industry-developed T90 anterior codend section improve size or species selection and fish quality compared to a traditional T0 codend?	Two 94-mm SMO codends: the first with a T90 anterior section and a posterior T0 section; and the second entirely made from T0 mesh (Figures 2 and 5a).	Six days and nights with 12 deployments per codend.	7 and 17
Two	CTS, from Ulladulla and Bermagui	Do key target, by-product and bycatch species have divergent vertical distributions in typical trawls, and might this information be used to improve selectivity?	Two treatments in a conventional two-seam trawl: the first rigged with a horizontal aft separator panel leading to two codends; and the second without the separator panel and just the two codends (Figure 6).	Ten days with 17 and 15 deployments for each configuration.	8 and 17

Phase	*Fishery and location*	*Questions asked?*	*Treatments*	*Total no. of days and deployments per treatment*	*Appendix*
Three	GABTS, from Port Lincoln	Does larger T90 mesh in the anterior codend section and throughout improve size (for Deepwater Flathead ≥ 40 cm TL) and species selectivity compared to an industry-developed T90 codend?	Three T90 codends: the first was the industry-developed design comprising an anterior section of 94-mm T90 and a posterior section of the same mesh as T0; the second was 100-mm T90 in the same anterior section; and the third was 100-mm T90 throughout (Figures 2 and 5b). An 85-mm T0 codend was also fished separately.	11 days and nights with six or seven replicates of the T90 codend and 10 replicates of the T0 codend.	9, 10 and 17
Three	CTS, from Ulladulla	Do smaller-meshed T90 codends and their circumference improve size or species selection compared to a conventional T0 codend?	Three codends: the first was the conventional 91-mm T0 design; the second and third were made from 71-mm T90 mesh with narrow (66% of stretched conventional codend) and wide (100%) circumferences (Figures 2 and 7).	13 days, with 12 replicates of each codend design	11 and 17
Three	CTS, Ulladulla and Bermagui	Does headline height affect the size or species selectivity of two-seam trawls?	Two trawls with different headline heights: conventional (~3.8 m); and low (~2.8 m).	12 days, with 24 and 23 replicates of the conventional and low trawls	12 and 17

As an adjunct to the phase-2 and -3 experimental work, in collaboration with the CSIRO, we sought to investigate the potential impact of any future changes in gear selectivity to reduce the unaccounted fishing mortality on key SESSF stocks. Specifically, we used management strategy evaluation (MSE) to evaluate the impacts of selectivity changes on the assessment bias and the subsequent sustainability and economic performance of Tiger Flathead, Eastern School Whiting, and Redfish, *Centroberyx affinis*; species with quite different life histories and exploitation characteristics. The analyses of this ancillary work is described in Appendix 13.

Data collected during the manipulative experiments in phases 2 and 3, and statistical analyses

Various technical and biological data were collected during each experiment. Technical data included ~20 replicate measurements of mesh sizes in codends, lengtheners/extensions and/or trawls before fishing. During fishing we recorded the start and end times of each deployment (otter boards on and off the bottom), depths (m), total distance trawled (m; from a global positioning system: GPS plotter), average speed over the ground (SOG; ms^{-1}), wing end and/or otter-board spreads (m) and, if required, headline height (m). The latter three variables were recorded using either Notus or Scanmar trawl-monitoring equipment.

At the end of each deployment, catches were brought onboard and separated if required (i.e. where a cover or dual codends were fished; Appendices 5 and 7) into on-deck holding areas. The total catch weight was calculated based on either the known volumes of the holding area or the codend. Retained catches were separated by species and placed into 55-l boxes before being weighed, counted and the most abundant measured for their TL (to the nearest 0.5 cm). The known weight of retained catch was either subtracted from the total to provide the total discarded catch, or the latter was weighed in its entirety. Either all, or a subsample, of the discarded catch was identified to species level, counted and weighed (and numbers or weights extrapolated as required). Randomly selected subsamples of key fish were then measured as above.

The technical data were analysed using linear mixed models (LMM), and often with covariates such as ‘depth’ and ‘SOG’, in addition to the gear ‘treatment’ of interest. Random effects always included ‘days’. The most appropriate models were chosen using backward selection, whereby non-significant fixed effects were removed until all remaining terms were significant.

Standardized (ha^{-1} trawled using the otter-board spreads) weights of key species and combined catches were analysed using either LMMs (with data log-transformed to act multiplicatively) or the Tweedie distribution (which innately incorporates zero inflation in non-negative numeric data and is fitted on the log scale) fitted using generalized linear mixed models (GLMMs). All models included the same random terms as for those assessing technical variables and were fitted using the glmmTMB function from the R package of the same name (R, Core Team, 2021). The statistical significance of fixed effects for the treatments of interest was evaluated at the 5% level using Wald tests, and where there were more than two treatments, any significant effects were separated using the Benjamini-Hochberg-Yekutieli procedure to control the false discovery rate (FDR; Benjamini and Hochberg, 1995).

In addition to the mixed-effects models assessing technical data and catches, in all experiments generalized additive modelling (GAM) was used to fit relative selectivity curves to the length-frequency data of species caught and measured in sufficient numbers. Length frequencies were first scaled up by deployment subsampling fractions to estimate total frequencies. Relative selectivity was assessed for all possible pairings of all treatments (i.e. a maximum of three).

As an example, for those deployments involving treatment A and B codends, let n_l^A and n_l^B denote the number of length l fish caught in those gears. Then

$$p_l = \frac{n_l^B}{n_l^A + n_l^B}$$

is the proportion caught in the B gear. The expected value of p_l was modelled on the logit scale using cubic regression splines of dimension three, denoted *s(l)*. That is

$$E[p_l] = \frac{\exp(s(l))}{1+\exp(s(l))}$$

The error distribution of p_l was specified to be quasi-binomial to incorporate overdispersion arising from subsampling of catches. The GAMs were fitted in R using the gam function within the mgcv package (Wood, 2017). Confidence intervals around the fitted splines were obtained using a 1000 iteration double bootstrap whereby the relevant tows were first resampled, followed by resampling of the length frequencies within each selected trawl (Millar, 1993; Xu and Millar, 1993). This catch-comparison analysis was implemented using the SELECT R package which includes bootstrap functionality to allow for between-haul variability (Millar et al., 2004; 2021). Permutation tests were also used (1000 resamples) to assess for any statistical significance of treatments.

In one experiment (Appendix 6), a covered-codend approach was applied to a relevant treatment and deployments fitted via maximum likelihood using the SELECT function within the R package of the same name (Figure 8, Wileman et al., 1996; Millar, 2001). The choice of selection curve (logistic or Richard's) was made by assessing residual plots and fits confirmed via visual examination of deviance residuals and by comparing adjusted model deviances and associated degrees of freedom with a chi-squared distribution (Millar and Fryer, 1999). The model deviances were adjusted for over-dispersion due to between-haul variation using the replicate estimate of dispersion (Millar and Fryer, 1999). Confidence intervals for the parameters of interest (50% probability of retention; L_{50} and selection range; SR) for the best model were obtained using a double bootstrap to incorporate both between- and within-haul variabilities. Ten thousand bootstrap simulations were performed. Pointwise 95% confidence intervals for the retention probability at any given length were similarly obtained.

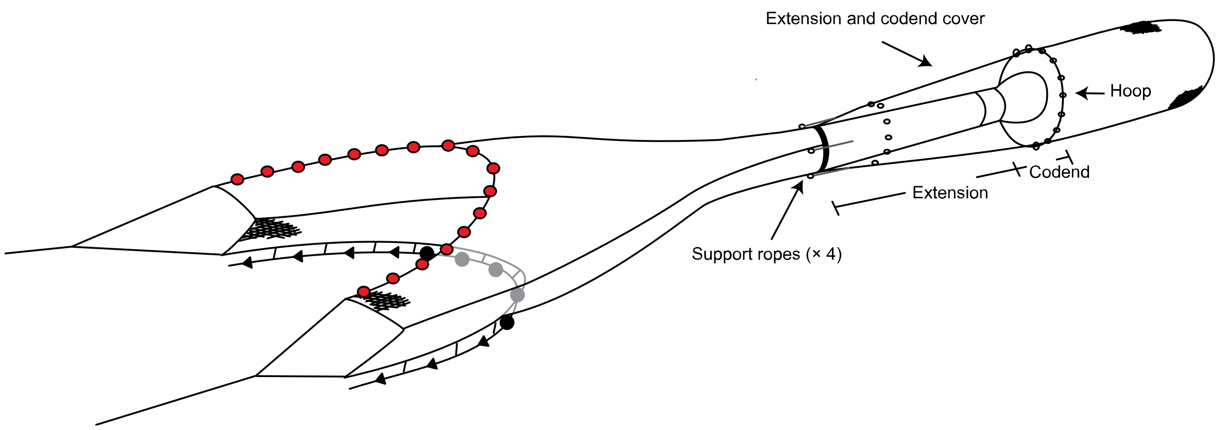

Figure 8. Representation of the codend cover tested during an experiment in phase 2 (Appendix 6).

Results

Phase 1: national review

The national review is presented in Appendix 3, and was distributed to fishers as a summary in Appendix 14. This review details 11 separately managed fish-trawl fisheries around Australia, encompassing 118 licenses, of which ~84 (71%) were active at the time of writing. The CTS (26 active licences) and GABTS (three active) accounted for some 35% of the total number of Australian fish-trawl licenses, while inshore NSW vessels comprising the northern and southern fish-trawl fisheries (the latter overlapping some of the same latitudes as the CTS) contributed a further ~50%. These numbers reiterate the focus of examining fish-trawling off the temperate, south-eastern and southern Australian coasts. Such effort concentration, combined with ongoing selectivity issues have precipitated most of the historical research into reducing bycatch in Australian fish trawls.

More specifically, over the past 25 years there have been seven projects aimed at assessing and/or extending modifications to fish trawls throughout south-eastern and southern Australia. The largest investment in research has come from the FRDC (two multi-year projects), although NSW DPI and AFMA have also funded short-term (i.e. single experiments) studies in response to regional priorities. Other short-term work (three projects) has been done to investigate the utility of mechanical separators (e.g. grids) for excluding listed megafauna in other Australian fisheries, including Western Australia. Finally, survey work and log-book data have included descriptions of the gears used and configurations of trawls off south-eastern Australia. These various projects have supported several management changes to the technical aspects of trawls, and mostly in NSW inshore waters and the CTS and GABTS.

Based on logbook data, the national review revealed that gear configuration details were not consistently or well recorded over time, but nevertheless showed considerable historical variability among chosen trawl configurations in the CTS and GABTS, including different codend mesh sizes and the use of BRDs, which demonstrates industry willingness to independently pursue options beyond the legislated minimum requirements. In recent years, most fishers appear to have used 90–100 mm SMO codends made from single twine, which do not require a concomitant BRD (T45 or T90 panels). Nevertheless, log-book data and observer work implies operators have trialled various codends, including full T45 or T90 designs, and apparently in response to spatio-temporal bycatch issues. The utility of modifications in terms of size and/or species selectivity is not easily deciphered from log-book or observer data, and requires further assessment via applied manipulative experimentation. However, the multiple logs of some alternative configurations imply minimal perceived target/by-product species loss by operators. It is also evident from the international review that many subtle but effective modifications, and especially to trawl rigging would not be captured by log books or observers. Further, many operational or behavioural changes implemented to avoid high levels of bycatch are not well documented.

All types of trawl modifications tested in the CTS, GABTS and among Australian fish-trawl fisheries identified in the national review encompassed the same designs as earlier modifications tested in overseas fisheries, which were identified during the international review. It was clear that the few Australian efforts at improving regional fish-trawls have closely followed ideas developed in other countries. Specific details about the types of modifications, their classifications and ultimate utilities are summarised below.

Phase 1: international review

More than 300 papers published between 1992 and 2020 were located using the international-review search terms, but 100 papers were excluded because they did not satisfy the required criteria (manipulative experiments assessing modifications to improve fish-trawl size and/or species selectivity). A remaining 203 papers were identified as appropriate, and so formed the basis of the review (Appendices 4, 14 and 16). These studies encompassed most of the world's oceans, and involved ~150 species, although there was a strong bias towards Europe (74% of studies) and, by default, the key species studied were Haddock, *Melanogrammus aeglefinus* and Atlantic Cod, *Gadus morhua* (Figure 9). North America accounted for most of the remaining studies. Only 3% of published papers described efforts to improve the size and/or species selection of fish trawls in Australia, which was among the lowest outputs for developed countries with fish-trawl fisheries comprising multiple vessels (Figure 9).

To consolidate the diversity of modifications, a generic fish trawl was divided into four zones: zone 1 = spreading mechanisms (warps, otter boards, sweeps and bridles); zone 2 = headline, foot rope and ground gear; zone 3 = wings and body; and zone 4 = extension/lengthener and codend (Figure 10). Each of the four zones were subjected to various simple and complex modifications designed to exploit either the assumed behaviour and/or swimming capacity of key species (mostly zones 1 to 3), or their known sizes and/or morphology (mostly zone 4). In some cases, modifications were assessed across zones. Summaries of key zone-specific modifications are listed below.

Zone 1

Only 7% of published studies investigated changes to spreading mechanisms, and these mostly focused on raising sweeps off the bottom, changing warp, sweep or bridle lengths and angles, or the spread ratios of trawls. Zone-2 modifications reduced the catches of some species (especially flatfish); albeit with no major effects on the sizes caught. Raised sweeps had greater diurnal than nocturnal effects, attributed to visual responses to the stimuli.

Zone 2

Slightly more (11%) studies investigated changing the headline, foot rope and ground gear, which included raising foot ropes using floats; spokes; larger and/or wider spacing of discs, so-called 'rockhopper' and 'semicircular spreading ground gear' and alternate light (rubber) ground gears with rollers or large rubber discs, or with/without tickler chains. Some of these modifications reduced the catches of unwanted sizes of certain species, especially so-called 'round fish' with a height-to-width ratio >1 (like Haddock and Atlantic Cod), but less so for 'flat fish', with height-to-width ratios < 1 (e.g. Dover Sole, *Microstomus kitt*).

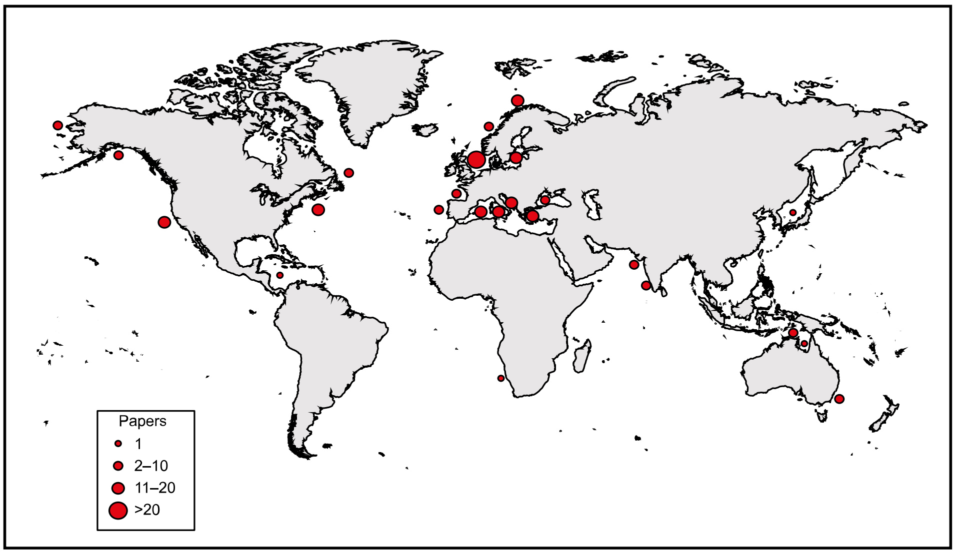

Figure 9. Map showing the locations and numbers of studies published in international journals assessing technical modifications to improve the size and/or species selectivity of fish trawls between 1992 and 2020 (Appendix 4).

Lower headline heights on trawls reduced the catches of Atlantic Cod but maintained catches of flat fish. Raised foot ropes (creating more height above the ground gear; Figure 1) reduced the bycatches of some unwanted benthic fish and infauna. Discs on the ground gear (Figure 3) increased the catches of flat fish and reduced the catches of Atlantic Cod. Similarly, ground-gear rollers decreased the catches of invertebrates, debris and sometimes, smaller sizes of target species. Removing a tickler chain from in front of the ground gear reduced the catches of unwanted elasmobranchs, but also generally resulted in fewer targeted flat fish being caught. Some studies also investigated lights (typically Lindgren-Pitman Electralumes® comprising green light emitting diodes; LEDs) at the frame lines, but with variable success.

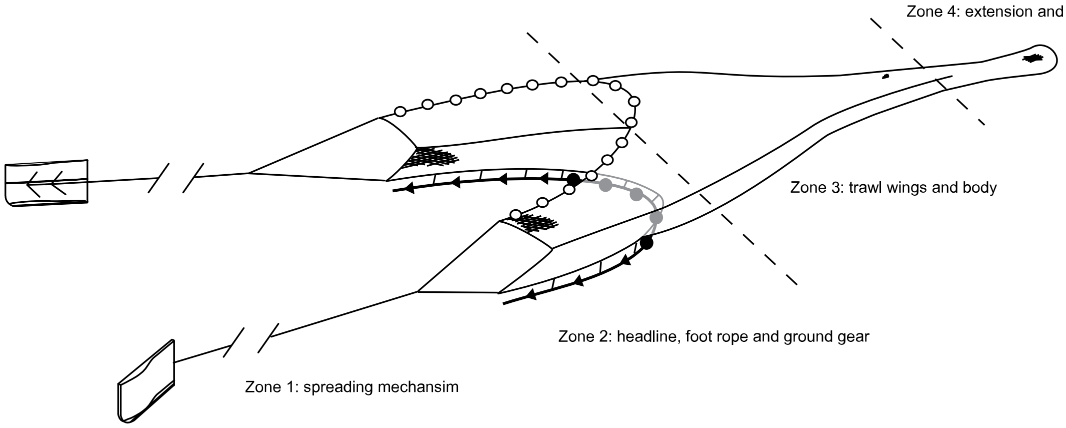

Figure 10. A generic fish-trawl showing the zones in which modifications were classified for the purposes of the international review.

Zone 3

Similar to zone 2, efforts at modifying zone 3 (the trawl wings and body) comprised only 11% of the total. The types of modifications included simply increasing mesh size throughout conventional T0 netting, horizontal-separator panels/frames in the trawl (some from the headline through to extension and with dual codends; Figure 5) and windows in various parts of the trawl body (some with guiding panels). Larger mesh sizes and trawl-body windows were all effective at reducing the catches of unwanted sizes while maintaining target catches; and especially windows for flat fish depending on the location.

Zone 4

Modifications to zone 4 (the extension/lengthener and codend) were by far the most common, comprising some 70% of all efforts. The types of modifications varied, but usually included increasing codend lateral-mesh openings via larger T0 meshes, similar-sized or smaller T45 and T90, or maintaining T0 mesh sizes but reducing codend circumferences or twine diameters. Other effective zone-4 modifications involved removing external attachments like chafing bags and inserting windows of larger T0 meshes. In some cases, grids were inserted to achieve either better species selection (e.g. to reduce the catches of large elasmobranchs) or size selection (and allow small fish to escape). Other, less common, zone-4 modifications included deflector funnels to guide fish to escape points, and mechanisms to release fish from codends at certain depths, or when catches reach a certain level using acoustic releases, weak links or pre-set holes.

Of the zone-4 changes, entire codends made from alternative mesh sizes and shapes (usually T45) often improved size selectivity, especially for round fish and usually because the conventional T0 meshes were simply too small. But in some cases, there were issues with relatively lower strength and flexibility in T45 codends. This latter issue was avoided by using smaller windows of alternate mesh shapes in conventional T0 codends or strengthening ropes (termed ‘lastridge’ ropes) which were sometimes shorter (by 70–90%) to help maintain lateral-mesh openings. Grids also were used to exclude larger species, but there was less application for improving size selection. In some cases, simpler modifications provided the same benefits, and with less complexity. There was also a lot of repetition among zone-4 modifications in some fisheries (especially those in Europe), which despite often positive prose in the various scientific papers, probably indicated that many problems remained unresolved.

Context of the reviews for applied experiments in the CTS and GABTS

Specific details concerning the reviewed modifications and their utility are provided in Appendix 4. These studies were used to propose a framework for assessing modifications in fish trawls, which is summarized in the Discussion section here. The history of work also helped to delineate coherent options for testing in the CTS and GABTS, although the first trials (project phase 2) were dictated by industry practice and modifications within conventional configurations. Rather, the options tested during phase 3 were more influenced by the international review. Considering the dearth of primary literature describing attempts at improving the size and/or species selectivity of Australian fish trawls, reports describing all experiments (even null effects) were submitted for publication in high-profile journals.

Phases 2 and 3: experimental work

In total, during seven field-based experiments (four and three for phases 2 and 3), we completed 82 days and 205 deployments. Across all experiments, in both fisheries, 77 species were retained (in varying proportions) and, to encompass target and by-product, were listed as 'commercial' while 88 species were always discarded as 'non-commercial' (Tables 2 and 3). Discarding was greater in the GABTS (~70%) than the CTS (encompassing NSW inshore) (Table 4). Many discards were small teleosts, but during all experiments, between ~30 and 77% (by weight) were elasmobranchs, with several species comprising individuals quite larger than most of the commercial species (Tables 2 and 3). All Latin names are included in Tables 2 and 3 and are not used from here on in this text.

During both phases, the various experiments involved assessing modifications to zones 2–4 of the trawls. For simplicity, these results are separated below in chronological order during each phase.

Phase 2: modifications within existing configurations

Considering the national review and industry priorities, the first experiment in phase 2 involved comparing three centre-third (13 m) ground-gear disc diameters (4 vs 7 vs 10 inches) on the same trawl in the CTS (i.e. zone-2 modification; Table 2; Appendices 5 and 17). The chosen disc diameters encapsulated the range used by nearly 90% of all CTS trawlers (determined via a previous survey; and also applicable to GABTS vessels) and were tested because there was a perception that increasing diameter would allow some small fish to escape under the ground gear (owing to the relatively higher foot rope). Also, inshore NSW trawlers are prohibited from using discs >100 mm diameter and there were concerns this configuration would be associated with greater bycatches of juveniles of CTS targets and negatively impact stocks.

During 12 deployments of each treatment over 12 days, there were no effects of ground-gear configuration on the otter-board spreads or headline heights of the trawl (Table 3); parameters that were only affected by the fishing depth (+ effect on otter board spread) and SOG (– effect on headline height). Similarly, there were no significant effects of ground-gear configuration on catches of any species nor their sizes, although for retained Bigeye Ocean Perch and discarded Falseband and Smooth Whiptails, the average catches were slightly lower (but quite variable) in the trawl when rigged with the 7- and 10-inch, than with the 4-inch ground gear.

Table 2. List of identified commercial (target and by-product) species caught during seven experiments in the Commonwealth trawl sector (CTS; and inshore NSW) and the Great Australian Bight Trawl Sector (GABTS).

Teleosts	*CTS*	*GABTS*
Australian Bonito, *Sarda australis*	Yes	No
Banded Rockcod, *Epinephelus ergastularius*	Yes	No
Bight Redfish, *Centroberyx gerrardi*	No	Yes
Bigeye Ocean Perch, *Helicolenus barathri*	Yes	Yes
Blackspotted Gurnard Perch, *Neosebastes nigropunctatus*	No	Yes
Blue Mackerel, *Scomber australasicus*	Yes	Yes
Blue Morwong, *Nemadactylus valenciennesi*	Yes	Yes
Blue Warehou, *Seriolella brama*	Yes	No
Bluespotted Flathead, *Platycephalus caeruleopunctatus*	Yes	No
Bluestriped Goatfish, *Upeneichthys lineatus*	Yes	No
Common Gurnard Perch, *Neosebastes scorpaenoides*	Yes	No
Common Stargazer, *Kathetostoma leave*	Yes	No
Conger Eel, *Conger verreauxi*	No	Yes
Deepwater Flathead, *Neoplatycephalus conatus*	No	Yes
Eastern School Whiting, *Sillago flindersi*	Yes	No
Fourspine Leatherjacket, *Eubalichthys quadrispinis*	Yes	No
Frostfish, *Lepidopus caudatus*	Yes	No
Gemfish, *Rexea solandri*	Yes	Yes
Giant Boarfish, *Paristiopterus labiosus*	Yes	No
Grey Morwong, *Nemadactylus douglasii*	Yes	Yes
Harpuku, *Polyprion oxgeneios*	No	Yes
Jack Mackerel, *Trachurus declivis*	Yes	Yes
Jackass Morwong, *Nemadactylus macropterus*	Yes	Yes
John Dory, *Zeus faber*	Yes	Yes
Knifejaw, *Oplegnathus woodwardi*	No	Yes
Latchet,	Yes	Yes
Longfin Bigeye, *Cookeolus japonicus*	Yes	No
Mackerel Tuna, *Euthynnus affinis*	Yes	No
Mirror Dory, *Zenopsis nebulosa*	Yes	No
Mosaic Leatherjacket, *Eubalichthys mosaicus*	Yes	No
Mulloway, *Argyrosomus japonicus*	Yes	No
Ocean Jacket, *Nelusetta ayraud*	Yes	Yes
Pink Ling, *Genypterus blacodes*	Yes	No
Red Cod, *Pseudophycic palmata*	Yes	Yes
Red Gurnard, *Chelidonichthys kumu*	Yes	No
Redfish, *Centroberyx affinis*	Yes	No
Reef Ocean Perch, *Helicolenus percoides*	Yes	No
Rudderfish, *Centrolophus niger*	Yes	No
Samsonfish, *Seriola hippos*	No	Yes
Silver Dory, *Cyttus australis*	Yes	No
Silver Trevally, *Pseudocaranx georgianus*	Yes	Yes
Silver Warehou, *Seriolella punctata*	Yes	No
Snapper, *Chrysophrys auratus*	Yes	No
Splendid Perch, *Callanthias australis*	Yes	No
Spotted Bigeye, *Priacanthus macracanthus*	Yes	No
Swordfish, *Xiphias gladius*	Yes	No
Tailor, *Pomatomus saltatrix*	Yes	No
Tiger Flathead, *Platycephalus richardsoni*	Yes	No
Tusk, *Dannevigia tusca*	No	Yes
Yellowspotted Boarfish, *Paristiopterus gallipavo*	No	Yes
Yellowtail Kingfish, *Seriola lalandi*	Yes	No
Yellowtail Scad, *Trachurus novaezelandiae*	Yes	No
Yellowfin Tuna, *Thunnus albacares*	Yes	No
Elasmobranchs		
Australian Angelshark, *Squatina australis*	No	Yes
Blackfin Ghostshark, *Hydrolagus lemures*	Yes	Yes
Banded Wobbygong, *Orectolobus halei*	No	Yes
Broadnose Shark, *Notorynchus cepedianus*	No	Yes
Bull Shark, *Carcharhinus leucas*	Yes	No

Common Blacktip Shark, *Carcharhinus limbatus*	Yes	No
Common Sawshark, *Pristiophorus cirratus*	Yes	Yes
Eastern Angel Shark, *Squatina albipunctata*	Yes	No
Eastern Shovelnose Ray, *Aptychotrema rostrata*	Yes	No
Elephantfish, *Callorhinchus milii*	No	Yes
Gummy Shark, *Mustelus antarcticus*	Yes	Yes
Ornate Angelshark, *Squatina tergocellata*	Yes	Yes
School Shark, *Galeorhinus galeus*	No	Yes
Sharpnose Sevengill Shark, *Heptranchias perlo*	No	Yes
Southern Eagle Ray, *Myliobatis tenuicaudatus*	Yes	Yes
Southern Sawshark, *Pristiophorus nudipinnis*	Yes	No
Spotted Wobbegong, *Orectolobus maculatus*	Yes	Yes
Whiskery Shark, *Furgaleus macki*	No	Yes
Cephalopods		
Cuttlefish, *Sepia* spp.	Yes	Yes
Gould's Squid, *Nototodarus gouldi*	Yes	Yes
Octopus, *Octopus* spp.	Yes	No
Pale Octopus, *Octopus pallidus*	Yes	No
Southern Calamari, *Sepioteuthis australis*	Yes	Yes
Gastropods		
Australian Tulip Shell, *Australaria Australasia*	Yes	No
Dog Whelks, *Nassarius* sp.	Yes	No
False Bailer Shell, *Livonia mammilla*	Yes	No
Arthropods		
Eastern Balmain Bug, *Ibacus peroni*	Yes	No
Royal Ped Prawns, *Haliporoides sibogae*	Yes	No

Table 3. List of non-commercial (bycatch) species caught during seven experiments in the Commonwealth trawl sector (CTS; and inshore NSW) and the Great Australian Bight trawl sector (GABTS).

Teleosts	*CTS*	*GABTS*
Australian Burrfish, *Allomycterus pilatus*	Yes	Yes
Australian Sardine, *Sardinops sagax*	Yes	No
Barracouta, *Thyrsites atun*	Yes	Yes
Barred Grubfish, *Parapercis allporti*	Yes	No
Beaked Salmon, *Gonorynchus greyi*	Yes	No
Bighead Gurnard Perch, *Neosebastes pandus*	No	Yes
Bigspine Boarfish, *Pentaceros decacanthus*	Yes	No
Blackspot Boarfish, *Zanclistius elevatus*	Yes	Yes
Blacktip Cucumberfish, *Paraulopus nigripinnis*	Yes	No
Black Jewfish, *Protonibea diacanthus*	Yes	No
Butterfly Gurnard, *Lepidotrigla vanessa*	Yes	No
Bulldog Stargazer, *Xenocephalus armatus*	Yes	No
Cocky Gurnard, *Lepidotrigla modesta*	Yes	Yes
Common Conger Eel, *Conger wilsoni*	Yes	No
Common Bellowsfish, *Macroramphosus scolopax*	Yes	No
Common Gurnard Perch, *Neosebastes scorpaenoides*	No	Yes
Common Stinkfish, *Foetorepus calauropomus*	Yes	No
Common Veilfin, *Metavelifer multiradiatus*	No	Yes
Cosmopolitan Rubyfish, *Plagiogeneion rubiginosum*	No	Yes
Deepsea Flathead, *Hoplichthys haswelli*	Yes	No
Deepwater Stargazer, *Kathetostoma nigrofasciatum*	No	Yes
Eastern Smooth Boxfish, *Anoplocapros inermis*	Yes	No
Falseband Whiptail, *Coelorinchus maurofasciatus*	Yes	No
Finespine Pufferfish, *Tylerius spinosissimus*	Yes	No
Fourspine Leatherjacket, *Eubalichthys quadrispinis*	No	Yes
Frostfish, *Lepidopus caudatus*	Yes	No
Globefish, *Diodon nicthemerus*	Yes	No
Ling's Armour Gurnard, *Satyrichthys lingi*	Yes	No
Little Whiptail, *Coelorinchus gormani*	Yes	No
Manyband Sole, *Zebrias scalaris*	Yes	No
Mosaic Leatherjacket, *Eubalichthys mosaicus*	No	Yes

Painted Latchet, *Pterygotrigla andertoni*	Yes	No
Pike, *Dinolestes lewini*	Yes	No
Pipefish, Syngnathidae	Yes	No
Prickly Toadfish, *Contusus brevicaudus*	Yes	No
Redbait, *Emmelichthys nitidus*	Yes	No
Red Cod, *Pseudophycis bachus*	No	Yes
Ringed Toadfish, *Omegophora armilla*	No	Yes
Rough Flutemouth, *Fistularia petimba*	Yes	No
Rough Golden Toadfish, *Lagocephalus lunaris*	Yes	No
Round-snouted Gurnard, *Lepidotrigla mulhalli*	Yes	No
Sandpaper Fish, *Paratrachichthys macleayi*	No	Yes
Sergeant Baker, *Latropiscis purpurissatus*	Yes	Yes
Spiny Boxfish, *Capropygia unistriata*	No	Yes
Spiny Pipehorse, *Solegnathus spinosissimus*	Yes	No
Smooth Golden Toadfish, *Lagocephalus inermis*	Yes	No
Smooth Whiptail, *Malacocephalus laevis*	Yes	No
Shortspine Porcupinefish, *Cyclichthys orbicularis*	Yes	No
Spotted Armour Gurnard, *Satyichthys rieffeli*	Yes	No
Starry Toadfish, *Arothron firmamentum*	Yes	No
Striped Trumpeter, *Latris lineata*	Yes	No
Swallowtail, *Centroberyx lineatus*	No	Yes
Thetis Fish, *Neosebastes thetidis*	No	Yes
Velvet Leatherjacket, *Meuschenia scaber*	Yes	Yes
Whitebarred Boxfish, *Anoplocapros lenticularis*	No	Yes
Yelloweye Redfish, *Centroberys australis*	No	Yes
Elasmobranchs		
Australian Longnose Skate, *Dentiraja blacodes*	Yes	No
Australian Ghostshark, *Callorhincus millii*	Yes	No
Banded Stingaree, *Urolophus cruciatus*	Yes	No
Banded Wobbygong, *Orectolobus ornatus*	Yes	No
Bigeye Thresher Shark, *Alopias superciliosus*	Yes	No
Common Stingaree, *Trygonoptera testacea*	Yes	No
Coffin Ray, *Hypnos monopterygius*	Yes	No
Collar Carpetshark, *Parascyllium collare*	Yes	No
Eastern Fiddler Ray, *Trygonorrhina fasciata*	Yes	No
Eastern Shovelnose Stingaree, *Trygonoptera imitata*	Yes	No
Greenback Stingaree, *Urolophus viridis*	Yes	No
Greeneye Dogfish, Squalus sp.	No	Yes
Kapala Stingaree, *Urolophus kapalensis*	*Yes*	No
Melbourne Skate, *Spiniraja whitleyi*	Yes	Yes
Peacock Skate, *Pavoraja nitida*	Yes	No
Port Jackson Shark, *Heterodontus portusjacksoni*	Yes	Yes
Rusty Carpetshark, *Parascyllium ferrugineum*	Yes	yes
Sandyback Stingaree, *Urolophus buccelentus*	Yes	No
Sawtail Catshark, *Figaro boardmani*	Yes	No
Scalloped Hammerhead, *Sphyrna lewini*	Yes	No
Sevengill Shark, *Notorynchus cepedianus*	Yes	No
Short-tail Torpedo Ray, *Tetronarce nobiliana*	Yes	Yes
Smooth Hammerhead, *Sphyrna zygaena*	Yes	No
Smooth Stingray, *Bathytoshia brevicaudata*	Yes	Yes
Sparsely-spotted Stingaree, *Urolophus paucimaculatus*	Yes	No
Spikey Dogfish, *Squalus megalops*	Yes	Yes
Spotted Eagle Ray, *Aetobatus ocellatus*	Yes	Yes
Spotted Wobbygong, *Orectolobus maculatus*	Yes	No
Southern Fiddler Ray, *Trygonorrhina dumerilii*	Yes	Yes
Sydney Skate, *Dentiraja australis*	Yes	No
Tasmanian Numbfish, *Narcinops tasmaniensis*	Yes	No
Western Shovelnose Ray, *Aptychoterma vincentiana*	No	Yes
Whitebarreed Boxfish, *Anoplocapros lenticularis*	No	Yes
White Shark, *Carcharodon carcharias*	Yes	No
Whitespotted Skate, *Dentiraja cerva*	Yes	No
Wide Stingaree, *Urolophus expansus*	No	Yes
Yellowback Stingaree, *Urolophus suffavus*	Yes	Yes

Gastropods	CTS	GABTS
False Bailer Shell, *Livonia mammilla*	Yes	No
Arthropods	*CTS*	*GABTS*
Hermit Crab, *Sympagurus* sp.	Yes	No
Southern Rock Lobster, *Jasus edwardsii*	No	Yes
Mammals		
New Zealand Fur Seal, *Arctocephalus forsteri*	Yes	No

The second phase-2 experiment sought to test the utility of an industry-initiated BRD (zone 4) designed to exclude small Eastern School Whiting from inshore trawlers (and similar in concept to the SESSF mandated BRDs) and assess for any effects of a codend cover on generic trawl performance (Appendix 6). The latter also facilitated quantifying the selectivity of an existing codend used to target Eastern School Whiting in NSW inshore waters. The cover neither affected the trawl's wing-end spread nor its catching efficiency. Despite an SMO of 96 mm and a perimeter much larger than the girths of all Eastern School Whiting (11–26 cm TL), the conventional T0 codend had a low 50% size at retention (L_{50}) of 16.8 cm TL (selection range of 5.9 cm), which was close to the desired marketable length for this species and above the mean size at maturity ~15 cm TL.

The capture of small Eastern School Whiting by the conventional T0 codend was attributed to an excessive increase in circumference (from 100 to 200 meshes) and a legally permitted 'catch-separating' rope to restrict fractional mesh openings to <~21%. Replacing ~1/4 of the 96-mm SMO netting in the codend and anterior extension with a panel of T45 mesh (~42-mm SMO hung on the bar) improved size selection for Eastern School Whiting (by allowing some fish <~15 cm TL to escape). Increasing the size of mesh in the panel to ~47 mm hung on the bar might allow more smaller fish to escape.

The third phase-2 experiment was done in the GABTS and tested the utility of a T90 cylinder in the anterior codend (four seams with shortened lastridge ropes) made from the same-sized conventional 94-mm SMO mesh currently used by most vessels in the GABTS and a design exceeding the minimum specifications for BRDs in the SESSF (Appendices 7 and 17). Compared to the traditional T0 codend comprising 94 mm (double 4-mm diameter twine) throughout, the new T90 configuration made with ~3 m of the same mesh turned 90º in the anterior section did not significantly affect catches of any discarded or retained species, or sizes of the primary target, Deepwater Flathead.

The only significant impact of the T90 was a slightly improved quality of Deepwater Flathead (measured as fewer skin lesions), attributed to some release of abrasive debris from the codend. The absence of any effects of the T90 mesh on selection probably reflected the small mesh size relative to most key species and the thick twine (double 4 mm diameter), which would have negated some of the anticipated increases in lateral-mesh openings.

The fourth (and final) experiment in in phase 2 involved a horizontal separator panel in the posterior (aft) 50% body of a generic trawl leading to upper and lower codends (Figure 11, Table 4; Appendices 8 and 17). During 32 deployments, there were no significant effects of the separator panel on trawl geometry, which like above remained dependant on depth (+ relationship with otter-board spread). The height of the trawl at entry was ~3.7 m (Figure 11). Among the total catches (~20 t), 13 and eight commercial and non-commercial species/groups were caught in sufficient quantities for analyses (Table 4).

The commercial species entered the aft trawl body at varying heights, but many individuals, including the most abundant, Tiger Flathead, initially orientated low in the mid trawl, and then moved upwards at the aft trawl to present similar catches in each of the dual codends (Figure 11). Eastern School Whiting was the only commercial species to show the opposite behaviour, entering higher at the mid trawl before orientating downwards. Non-commercial catches were biased towards elasmobranchs (5.8 t or 46% of the total; Table 4) and all except Smooth Stingray mostly entered the lower posterior trawl, with proportionally fewer than commercial species eventually rising upwards (Figure 11).

Table 4. **Summary of the phase, fishery, treatments tested, overall catches and the effects on catches and/or sizes, and the appendix (App.) containing the relevant report. All mesh sizes refer to stretched mesh opening. CTS, Commonwealth Trawl Sector; GABTS, Great Australian Bight Trawl Sector; T0, diamond-shaped mesh; T45, meshes turned 45° (square-shaped); T90, meshes turned 90°; L_{50}, size at 50% selection; SR, selection range (L_{25}–L_{75}); and sp., species (which in some cases included both retained and discarded categories based on size). All T90 codends comprised four seams with shortened lastridge ropes (83% of stretched codend length) at each juncture.**

Phase	*Fishery and location*	*Treatments*	*Catches*	*Effects on weights and sizes*	*Comments*	*App.*
Two	CTS, from Ulladulla	100 mm (4 in.) vs 178 mm (7 in.) vs 252 mm (10 in.) centre third ground gears.	12.8 t retained (29 sp.) and 9.8 t discarded (24 sp. including 3 t of elasmobranchs).	No significant effects of ground gear on any catches or sizes. Nevertheless, the mean retained catches of Bigeye Ocean Perch and discarded whiptails were greatest in the trawl with the 4-in centre ground gear.	Substantial variability in catches, but the effects of ground gear did not appear to be very strong.	5 and 17
Two	NSW, from Ulladulla	Conventional 96-mm T0 with and without a 47-mm T0 cover vs same codend with a 42-mm T45 mesh panel.	15.2 t (not separated into retained and discarded catches) comprising >31 sp. in total. Elasmobranchs comprised 5 t of the catch.	The cover had no effects on trawl performance. The conventional 96-mm T0 codend had a L_{50} and SR of 16.8 and 5.7 cm TL for Eastern School Whiting. The T45 panel released some Eastern School Whiting <15 cm TL.	A larger T45 mesh panel was proposed (and permitted via permit) to increase the escape of small fish.	6
Two	GABTS from Port Lincoln	Traditional 94-mm T0 codend vs same posterior codend with an anterior cylinder of T90 (industry design) sewn in four seams and with shortened lastridge ropes.	19.1 t retained (18 sp.) and 39.4 t discarded (>68 sp. including ~30 t of elasmobranchs).	No significant effects of codend configuration on any catches or sizes. But the 'quality' (ventral colour and number of cuts) of Deepwater Flathead caught by the T90 codend was significantly better.	Regardless of configuration (T0 or T90), the mesh size was not large enough to affect catches of any species. The improved quality of Deepwater Flathead was attributed to more debris being released from the codend.	7 and 17
Two	CTS from Ulladulla and Bermagui	Trawl with a horizontal-separator panel leading to dual codends vs same trawl with dual codends only.	7.7 t retained (>46 sp.) and 12.1 t discarded (>33 sp. including 5.8 t of elasmobranchs).	Most target species entered the trawl low and eventually rose up quite strongly while several key unwanted species (rays and skates) maintained relatively lower orientations.	Species-specific differences in vertical orientations might facilitate excluding some unwanted catches via modified gears.	8 and 17

Phase	Fishery and location	Treatments	Catches	Effects on weights and sizes	Comments	App.
Three	GABTS from Port Lincoln	94-mm T90 anterior cylinder and 94-mm T0 posterior vs 103-mm anterior cylinder and 94-mm T0 posterior vs 103-mm T90 throughout.	14.7 t retained (>29 sp.) and 44.6 t discarded (>45 sp. including 14.7 t of elasmobranchs).	Both large-meshed codends caught fewer immature Deepwater Flathead, but also lost longer fish, especially the codend with 103-mm T90 throughout.	Recommended ~100 mm T90 in anterior section or ~94-mm throughout. But codend modifications will have limited effects. Anterior-trawl modifications will be required to substantially reduce bycatches.	9, 10 and 17
Three	CTS from Ulladulla	91-mm T0 throughout vs narrow 71-mm T90 vs wide 71-mm T90. Both T90 codends had shortened lastridge ropes	9.7 t retained (>62 sp.) and 18.3 t discarded (>49 sp. including 7.4 t of elasmobranchs).	Both T90 codends retained more Latchet than the 91-mm T90. The wide 71-mm T90 allowed more undersized Tiger Flathead (<28 cm TL) to escape than the narrow 71-mm T90.	The T90 mesh size was too small, but increasing circumference T90 codends with short lastridge ropes improved selection.	11 and 17
Three	CTS, from Ulladulla and Bermagui	Conventional (3.8 m) vs low (2.8 m) headline trawl	11.3 t retained (>43 sp.) and 16.9 t discarded (<67 sp., including 8.2 t of elasmobranchs).	No significant differences in catches between trawls, although mean weight of Tiger Flathead was lower in the low trawl. Regardless of trawl, the catches of two rays decreased with increasing headline height.	A slightly lower headline trawl than conventional (i.e. between 3.8 and 2.8 m) should maintain target catches, while reduce drag and therefore fuel.	12 and 17

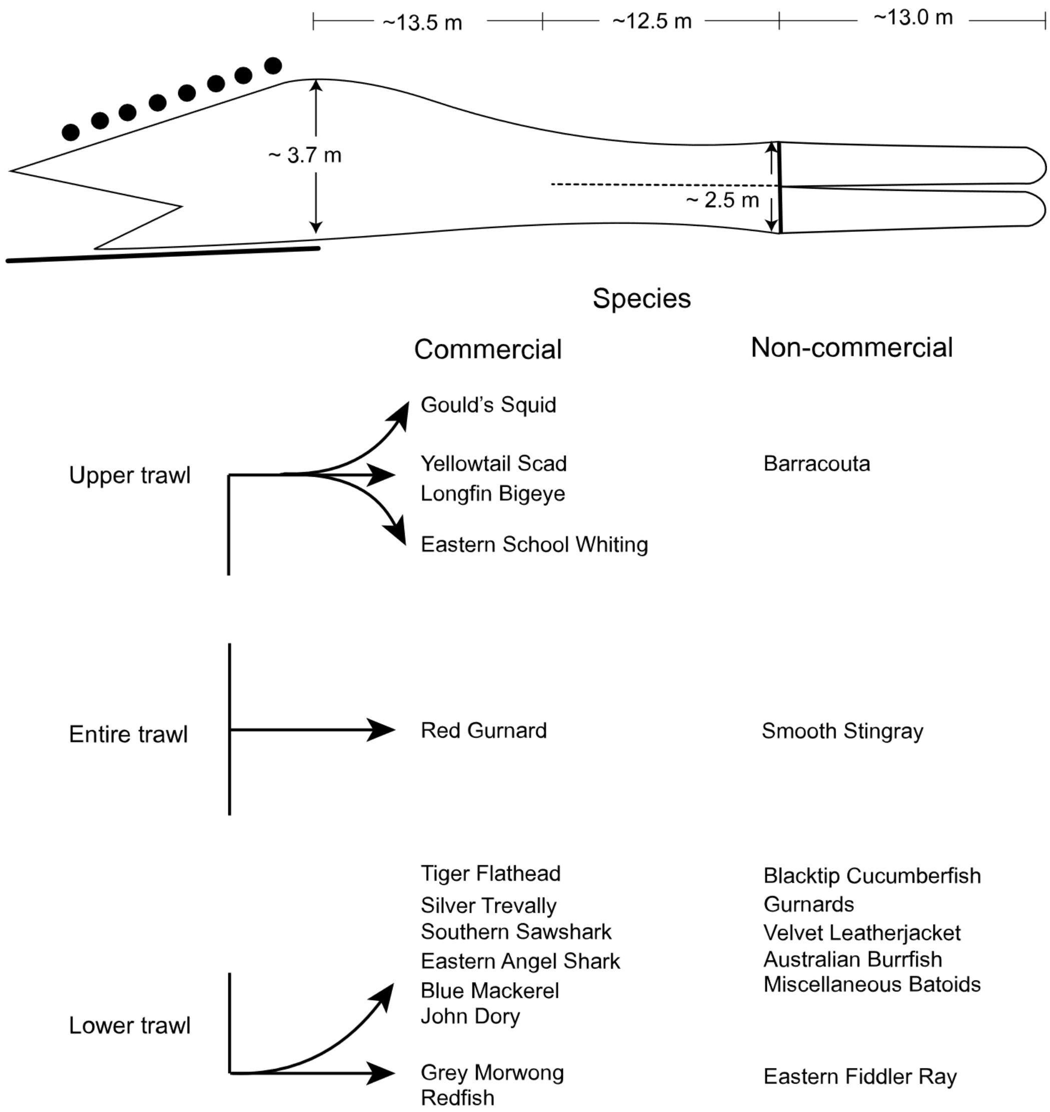

Figure 11. Side view of a CTS trawl with the horizontal-separator panel showing the average trawl heights and approximate stretched lengths of sections, and the general bias towards upper or lower (or neither) separated compartments for key species.

Phase 3: new modifications

The results from the first T90 experiment in the GABTS reiterated the need to better match mesh perimeter to the desired sizes of Deepwater Flathead prior to efforts at maximising lateral openings, and so during a subsequent experiment in phase 3, larger T90 mesh sizes were investigated (Appendices 9, 10 and 17). For this work, the conventional codend comprised 94-mm mesh throughout (double 4-mm diameter twine) with T0 orientation in the posterior half, but T90 in the anterior half ('half 94-mm T90' codend). The second and third codends had 105-mm T90 mesh in the anterior section only ('half 105-mm T90') and throughout the entire codend ('full 105-mm T90'), respectively and all with double 4-mm diameter twine).

Both new codends improved size selection for Deepwater Flathead, although the full 105-mm T90 reduced catches of individuals ≥40 cm TL. The new T90 designs also allowed some discarded species to escape, but similarly affected other targeted species. Data collected describing the morphology of deepwater flathead supported testing a T90 mesh size of ~100 mm in the anterior codend, or ~94-mm throughout to maintain target catches (≥40 cm TL). But, irrespective of any changes to codend meshes, owing to comparable inter-specific sizes and shapes, the high percentage of discards will probably remain consistent. This outcome was supported by additional data collected from an 85-mm conventional diamond-mesh codend conventionally fished by the vessel after the experiment which, notwithstanding confounded spatial and temporal deployments and despite retaining more smaller Deepwater Flathead, maintained a comparable percentage of total discards (i.e. ~70% of the total catch) (Appendix 9).

The final T90 codend trial was done in the CTS. While this mesh configuration is well established in the GABTS, there was limited log-book or observer evidence of application in the CTS and so the modification was deemed new. The results from this work showed for the first time that codend circumference had no negative effects on the size and/or species selection of T90 codend designs configured with shortened lastridge ropes. Rather, by providing more openings, the wider T90 codend allowed smaller Tiger Flathead to escape. Nevertheless, the tested mesh size (71 mm) appears slightly too small and future efforts with T90 codends in the CTS would be best suited to examining mesh sizes of ~75–80 mm, and ideally at stretched circumferences approaching 100% those of the conventional T0 codends.

The horizontal separator panel work precipitated the design of the final study in phase 3, involving the effects of headline height on target and bycatches in the CTS. The conventional trawl had a mean headline height (± SE) of 3.76 ± 0.07 m, while the low trawl (identical except for ~22% reduction in fishing circumference at the mouth) achieved 2.75 ± 0.07 m and across the same operational conditions (i.e. otter-board spread, fishing depth, towing speed, etc.). There were no significant differences in the numbers and weights of retained and discarded species between the two trawls, although mean catches of Tiger Flathead were ~25% lower in the low trawl, implying this species orientates across the range of heights fished conventionally. Regardless of the trawl, there was a significant, negative main effect of headline height on the weights of total discards and two abundant batoids: Smooth Stingray and Greenback Stingaree. These results were attributed to lower ground-gear contact pressure and/or an increased footrope height of both trawls, facilitating the escape of some individuals under the trawl. The only other species affected by headline height was Velvet Leatherjacket with catches increasing as headline increased; possibly owing to changes in netting panel angles at the trawl mouth that precluded escape.

Impacts of changing trawl selectivity on the stock statuses of three species

For Eastern School Whiting, Tiger Flathead and Redfish, two general cases of modified selectivity were assessed within both of which the discards reduce but selectivity of the retained catch (1) does not vary; or (2) improves. The implications of these two cases were modelled for eight assessment scenarios; specific details of which are provided in Appendix 13.

In general, for all three species, both cases of modified selection positively impacted sustainability, and with minimal reduced average catches. However, there were species-specific differences that reflected board life histories. Specifically, while stocks of the shorter-lived Eastern School Whiting and Tiger Flathead showed similar outcomes, Redfish (species with the greatest longevity and lowest natural mortality) had the lowest benefits associated with changing selectivity.

Discussion

This project describes the first multi-year assessment of selective modifications in Australian fish trawls in two decades and is only the second such project for trawlers working in the SESSF. While the data revealed minimal improvements in the size and/or species selectivity of conventional fish trawls within the existing treatments tested during phase 2, there were benefits of new modifications tested during phase 3 in terms of improving selection and that could have implicit positive outcomes for stocks. Further, based on the two definitive literature reviews, and especially the international effort, ongoing work to refine these new modifications and/or identify others that improve selection warrants following a framework that considers the benefits and limitations of previous experiments and their execution. This recommended framework is discussed prior to overviews and critique of the results from the various manipulative experiments in phases 2 and 3.

Phase 1: national and international reviews

It was clear from both reviews that, compared to most other developed countries with fish-trawl fisheries, there have been very few formal efforts at improving the size and/or species selectivity of Australian fish trawls. And certainly, within Australia, much less attentional has been directed towards fish than penaeid trawls. More specifically at the end of the 20th century, Broadhurst (2000) identified that Australian published studies accounted for >60% of global efforts to improve penaeid-trawl selectivity; a rate maintained in the ensuing two decades (McHugh et al., 2017). By comparison, the national review identified only two multi-year and five smaller Australian projects dedicated to developing fish-trawl modifications or their extension, for an ~3% contribution to the global published efforts.

The historically lower attention directed towards improving Australian fish-trawl selectivity probably reflects not only fewer vessels (~118 nationally) than those towing penaeid trawls (>1000), but also the perceived unaccounted fishing mortality issues, and particularly from the bycatch of ETP species. In response to legislated requirements to reduce the fishing mortality of marine turtles in the 1980s, developed countries with penaeid-trawl fleets (mostly Australia and the USA) devoted considerable resources towards researching effective BRDs and other penaeid-trawl modifications. A lack of similar impetus has probably limited efforts among Australian fish-trawl fisheries. Nevertheless, the general principles for resolving unaccounted fishing mortality via bycatch reduction remain similar in all trawl fisheries (Broadhurst, 2000; McHugh et al., 2017) and can be summarized for fish trawls within the framework presented in Table 5 with reference to both overseas fisheries and, in some cases, past efforts in the CTS and GABTS.

Prior to discussing the framework, regardless of the fishery or modifications tested, it is important to consider required commonality among experimental designs. First, field work should be designed with sufficient replication to answer the questions being asked (i.e. adequate power to test the stated hypotheses). Because nearly all of the world's fish-trawl fisheries involve single-rigged trawls, most experiments have involved either alternate hauls (where one treatment is alternately deployed against others, including a control) or covers over codends. Another method involving 'trouser trawls' (i.e. two codends on one trawl) has been identified as problematic in terms of treatment independence and is no longer used (i.e. only one published usage since 2009; Pol et al., 2016). Of the two valid methods, covered-codend approaches require much less replication, but covers should be tested for confounding effects because while none were observed in one experiment here (Appendix 6), confounding can occur and will affect data interpretation (Madsen and Holst, 2002). Second, adequate technical specifications of all tested modifications, trawls and fishing operations need to be provided in reports to ensure both replicability and to facilitate eventual legislation. The specified detail for such reporting is provided by Wileman et al. (1996). Third, the full range of coherent options/levels within a treatment should be investigated before accepting the hypothesis of no utility of that general type of modification (e.g. all disc sizes on a ground gear, or the range of coherent mesh sizes, etc.). And lastly, reports should be submitted to high-profile fisheries journals to achieve a sufficient level of scrutiny and standard in terms of analyses, interpretation, and conclusions.

In terms of modifications within any fishery, owing to homogeneity among codends, investigating appropriate lateral-mesh openings in zone 4 is the most coherent starting point. Doing so is usually straightforward because testing does not require trawl-monitoring equipment, codends are easy to alternate between deployments, and any specifications are easy to understand, implement and legislate (Tucker et al., 1997) (Table 5). More specifically, matching the most appropriate-sized T0, T45 or even T90 mesh to the desired sizes and shapes of the smallest key commercial species is a logical starting point, and especially for reasonably fusiform fish, which might include those species with a maximum height to width of >1 (Halliday and Cooper, 2000; Campos et al., 2003; Dereli and Aydin, 2016).

Table 5. A framework for choosing modifications to assess in demersal fish trawls derived from a review of the international literature. T0, diamond-shaped meshes; T45, meshes turned 45^{o} (i.e. square shaped); T90, meshes turned 90^{o}

Consideration	*Zone*	*Modifications to test in sequence*	*Advantages*	*Disadvantages*
First	4	o Choose the correct mesh size and shape for the smallest key target species. o Choose the narrowest possible codend circumference and twine diameter. o To reduce catches of round fish, locate escape windows as close as possible to the catch and on the top of the codend. o To increase fish entering escape exits, consider guiding panels/stimulants (e.g. green light emitting diodes for nocturnal fishing or deep water). o To reduce the bycatches of small fish in fisheries with very few target species, consider size-selective grids. o To exclude animals larger than the targeted species, consider species-selective grids.	o Simple changes usually improve selectivity. o This zone is usually common among fleets. o Changes can be flexible and easy-to-source. o Trawl monitoring equipment is not required to assess modifications.	o Modifications will not reduce drag or fuel usage. o Some modifications (e.g. T45 and T90 mesh) can alter their shapes and sizes through time. o Fish escape may occur after substantial interactions with the gear, leading to injuries and at least some mortality.
Second	1–3	o Choose the largest possible T0 mesh sizes throughout zone 3. o Choose a narrow twine diameter. o Use a horizontal-separator panel(s) to confirm species-specific behaviour in the trawl to inform the design of modifications. o Depending on species distributions inside the trawl, assess windows with different mesh shapes in the wings, or top panels. o To increase fish contact with panels/windows, consider guiding panels/stimulants (e.g. light emitting diodes). o Depending on the species distributions at the trawl, assess different types of ground gears. o Optimise bridle and sweep lengths. o Optimise the spread ratio of the trawl.	o Simple changes to these zones usually improve selectivity. o Changes can reduce drag and fuel usage. o Changes can be flexible and easy-to-source. o Unwanted fish often escape the trawl entirely and with presumed few mortalities.	o These zones are often not common throughout fleets. o It can be difficult to distinguish the key factors improving selectivity (i.e. confounding is an issue). o Trawl-monitoring equipment is usually required (to standardise different trawl performances).

Choosing an appropriate minimum mesh size simply requires data describing the girth of smallest key targets and then choosing a matching inside mesh perimeter (e.g. Appendix 11). Where existing T0 mesh sizes are already appropriate, or if there is industry resistance to alternative-mesh configurations, mandating a minimum codend circumference might be a simple option to maximise the selectivity of T0 codends (Reeves et al., 1992; O'Neill et al., 2008), but with fewer (if any) benefits for T90 (Appendix 11) or T45 (Sala et al., 2016)—a similar result found for penaeid trawls (Broadhurst and

Millar 2009). Narrow twine dimeters and/or avoiding double twine would similarly be appropriate options for all mesh configurations because increasing twine diameter forces narrower lateral openings (Graham et al., 2009) (Table 5). Usually, excessive twine diameters or circumferences in codends indicate the fishers believe the minimum mandated mesh size is too large for the target species.

In the CTS and GABTS, the smallest key targets are Tiger Flathead and Deepwater Flathead, respectively with minimum desired sizes of 28 and 40 cm TL (although the latter is not a legal size). Fish at these sizes have girths of ~127 and ~170 mm which, based on mesh perimeter, correspond to SMOs of ~65 and ~85 mm, respectively. Intuitively, these very different minimum target species sizes imply differential minimum mesh sizes, but both fisheries are regulated to the same 90 mm SMO in the codend. Clearly, 90-mm mesh can be configured to retain smaller species (and therefore excessive smaller individuals of the larger species), and simply because there are no restrictions on twine diameter (which are readily available in diameters of up to 8 mm for single and 6 mm for double twine).

In some fisheries, instead of changing the entire codend (which might affect strength or flexibility), installing relatively small windows in codends (mostly on the top or sides) made from meshes with wider lateral openings have had utility, but positioning is clearly important with locations closer to the catch the most beneficial (e.g. Graham and Kynoch, 2001; Graham et al., 2003) (Table 5). The positioning of BRDs in codends is not regulated in the CTS or GABTS, but has been discussed by Herrmann et al. (2015), who reaffirmed earlier research in penaeid trawls where displaced water was shown to assist fish to escape via proximal openings—providing the latter are within the areas of maximum water displacement from the codend (Broadhurst et al., 1999; 2002). Beyond mesh size and excessive twine diameter, the importance of such effects might explain why the 94-mm T90 mesh in the anterior codend did not improve size or species selection in a fish trawl tested in the GABTS (i.e. they were too far forward).

Rigid grids have also been successful zone-4 options in some European fisheries, although their choice needs be carefully considered with regard to fishery-specific characteristics (Table 5). That is, size-selective grids designed to exclude small fish can be useful in fisheries where there are only one or two fusiform targets (Larsen and Isaksen, 1993; Sardá et al., 2004), although in some cases simpler modifications like increasing the T0 mesh size in codends were shown to be equally effective (Jørgensen et al., 2006; Grimaldo et al., 2008). In contrast, and as for penaeid trawls, there are few alternatives for excluding ETP megafauna like seals and elasmobranchs other than via species-selective grids, although subtle refinements to bar shapes, sizes and designs are required to maintain catches of target fish (Vaspollo et al., 2019). There have been some previous efforts at developing species-selective grids for Australian fish trawls (Wakefield et al., 2017), including in the CTS (Knuckey et al., 2002). One limitation for CTS vessels is that many do not use stern ramps to pull the lengthener/extension and codend up onto, but rather have their net drums positioned aft, close to the transom, which would limit being able to effectively retrieve and deploy a grid, or any other solid structure and result in safety concerns for crews (Figure 12).

Once appropriate simple zone-4 modifications have been developed for a fishery, efforts can focus on investigating options for the anterior sections of the trawl (Table 5). Such modifications need to be isolated and tested with carefully considered experimental controls. Simple options tested in overseas fisheries involve entire trawl panels or windows with larger lateral-mesh openings (like those used in zone 4) and designed to partition species based on size, following contact evoked by exploiting species-specific behavioural responses (Milliken and DeAlteris, 2004; Bayse et al., 2016; Santos et al., 2016). The few studies imply many round fish rise up, while flat fish remain low; a characteristic which can be, and has been used to separate species using modifications like horizontal panels (Engås et al., 1998; Ferro et al., 2007) or removing sections of the top panel (i.e. the 'lead-ahead') (Chosid et al., 2008; Eayrs et al., 2017).

Figure 12. The back deck of a typical Commonwealth Trawl Sector fish trawler with dual net drums close to the transom.

The international review concluded that horizontal panels might also be useful in studies of unassessed trawls to provide information on the preferred orientations of the key species as a precursor to making simple changes to promote bycatch escape (He et al., 2008). This logic supported testing a horizontal-separator panel in a generic CTS trawl during phase 2 (below and Appendix 8). In some fisheries, light emitting diodes (LEDs, typically green or blue Lindgren-Pitman Electralumes®) might then also be tested to exploit any identified behavioural differences (Lomeli et al., 2018). For example, Southworth et al. (2020) used a T45 window with and without LEDs in the top body of a scallop trawl and showed that the non-illuminated window reduced catches of Haddock in shallow water while illuminating the panel in deep water reduced Haddock and flat fish catches (Table 5).

Notwithstanding the potential complementary benefits on overall trawl selection associated with modifying anterior sections, the reviewed studies indicated that considerable ancillary information concerning the behavioural subtleties of key species is needed and incorporating often wide spatio-temporal variability in key environmental parameters (Wardle, 1989). In addition to sufficient replication, approaches often require specialized equipment including cameras and/or sonar (Engås et al., 1998; Ferro et al., 2007). Further, changes to the anterior sections of trawl can affect the entire system geometry, including spread ratio (distance between wing ends; Figure 1) and headline height which means trawl-monitoring equipment must be used and any effects incorporated into analyses (Lauth et al., 1998). Failure to use such equipment during the few previous studies assessing anterior modifications in the CTS (e.g. Broadhurst and Kennelly, 1995; Koopman et al., 2009) and GABTS (e.g. Knuckey et al., 2008) limits conclusions over modification suitability—owing to the known confounding of different spread ratios and therefore areas trawled (Kennelly and Broadhurst, 2021). The implicit requirement to use trawl-monitoring equipment during the testing of zone 1–3 modifications often restricts independent attempts at resolving bycatch issues for many fishers, and should be carefully considered when collaborating with industry to progress new trawl deigns.

Nevertheless, the advantages of modifying the anterior trawl include minimizing escape mortalities because, unlike the close confines of zone 4, fish are less likely to contact netting or other animals and be injured or killed (Table 5). Further, because the anterior trawl dictates most of the system drag, there is considerable potential to reduce operating costs through so-called ‘low impact fuel efficient’ designs (LIFE; Suuronen et al., 2012) which can, in turn, facilitate modifications being adopted throughout fleets due to concomitant fuel savings (McHugh et al., 2017).

Investigating the utility of modifying the anterior sections of trawls used in the CTS and GABTS to improve size or species selection is likely to realize benefits, and so treatments were investigated during both phases of research in this project. However, because of the lack of earlier research and a perceived need to refine zone-4 modifications to optimise lateral mesh openings in both fisheries, we maintained a relatively stronger focus on these latter modifications. This work is discussed below in terms of the zones of focus (grouped as 'posterior' or zone 4 and 'anterior' or zones 2 and 3 modifications) across both phases of research.

Phases 2 and 3: experimental work

Posterior (zone 4) modifications: T90 and T45 mesh

The national review highlighted variation in the reported sizes of T0 mesh (typically 90–110 mm SMO) in codends used by CTS and GABTS fishers and apparently in response to area-specific targeting of key species. However, because Knuckey and Ashby (2009) already assessed the selectivity of these generic T0 (and some T45 configurations), the current project sought to expand on recent industry initiatives, and mostly with T90 mesh, although a novel T45 panel was tested in a trawl fished by an inshore NSW trawler.

The first T90 experiment was done in the GABTS (during phase 2), and the analyses failed to detect any significant effects on the size or species selection of Deepwater Flathead or any other dominant species in catches (Latchets, Ocean Jackets, or Bight Redfish) associated with placing an industry-developed cylinder of 94-mm T90 mesh (double 4-mm diameter twine) anterior to the codend—with the latter comprising the same mesh orientated as T0. Despite having an area >12× the required number of meshes for the AFMA legislated panel BRD, the double twine reduced the mesh perimeter to the point where it was less than the girths of most fish. While some Deepwater Flathead <40 cm TL and other smaller species might have had girths sufficiently small enough to pass through the T90 mesh (e.g. Latchets), as stated above, a negating factor may have been the position of the cylinder at ~2.5 m anterior to the end of the codend; perhaps too far forward to allow fish to maintain position at the more open meshes (Broadhurst et al., 1999).

The codend with the 94-mm T90 cylinder was associated with a significantly improved quality of retained Deepwater Flathead, which was assumed to have occurred because of less debris in the codend (which the open T90 meshes released), and therefore skin abrasion. Similar observations have been made in other fisheries (Brinkhof et al., 2021) and certainly are sufficient justification for ongoing commercial use of the T90 configuration. Nevertheless, ideally a T90 codend in the GABTS would also improve size and/or species selection, especially considering the observed discarding rates during the experiment and from longer-term AFMA observer data are excessive at 2–3× the global average (Pérez Roda et al., 2019; Kennelly, 2021).

The benefits to fish quality supported investigating slightly larger T90 mesh (105 mm, but still comprising double 4-mm diameter twine), and in both the anterior section ('half') and throughout ('full') the posterior codend during phase 3 in the GABTS. This slight increase in mesh size significantly affected size and species selection, manifesting as reductions in the catches of small Deepwater Flathead and some other species (e.g. Latchet and Ringed Toadfish), with a trend of progressively fewer fish in the larger half T90 codend, and then full T90 codend. For Deepwater Flathead, these changes were reasonably matched to their morphology and the likely probability of encountering meshes (i.e. increasing escape of small fish with an increasing number of T90 meshes). But the catches of some desired species (e.g. Red Gurnard and Yellow-spotted Boarfish) were also reduced.

Regardless of the mesh shape, the overlapping morphologies of many commercial and non-commercial species make it difficult to configure optimal mesh sizes for all species in any fish-trawl fishery. For the GABTS, a full T90 codend (or possibly the posterior section only) with a slightly smaller SMO than 105 mm, or singe rather than double twine in even smaller mesh might be appropriate for Deepwater Flathead. Specifically, if 4-mm diameter double twine is desired, then 94-mm T90 mesh throughout the codend might allow more individuals <40-cm TL to escape. Alternatively, increasing the double-twine T90 mesh to ~100 mm in the anterior section only and maintaining ~94-mm T0 mesh in the posterior codend might have some benefits. These mesh sizes might be reduced slightly, if single rather than double twine is used, but some smaller individuals of commercial species (such as Red Gurnard) might also escape which, combined with no legal requirement to release juvenile Deepwater Flathead, probably would preclude adoption.

Overlapping morphologies among commercial and non-commercial species mean that beyond allowing some small Deepwater Flathead to escape, T90 will probably not be a very effective modification for dramatically reducing bycatches while maintaining all target catches in the GABTS. And potentially, other simpler codend modifications could have comparable utility, including configuring traditional T0 codends (at existing mesh sizes) with shortened lastridge ropes or using larger T0 mesh without lastridge ropes. These types of codends are easier to make and cost less than T90 designs.

Unlike in the GABTS, the key target in the CTS (Tiger Flathead) is also among the smallest commercial species and has a minimum legal size (28 cm TL), which supported assessing smaller T90 mesh during phase 3. Based on the morphology of a 28-cm TL Tiger Flathead, a mesh size of 71 mm made from single 3-mm diameter twine was chosen (and at two codend circumferences). This mesh size and twine diameter are also similar as those used in CTS boat seines (i.e. 75 mm). There were some effects of codend configuration on the total weights of Tiger Flathead, but this was limited to the narrower 71-mm T90 codend catching more smaller fish than either the conventional 91-mm T0 or wide 71-mm T90 codends. Both T90 codends significantly increased the catches of small Latchets, which were retained. These results imply that the mesh size was probably too small for Tiger Flathead, but like in the GABTS, a less-than-optimal T90 mesh size can be offset by simply increasing the number of meshes. We concluded that a mesh size of up to ~80 mm (and single twine diameter) hung at T90 and ≥66% of the stretched circumference of the conventional 90-mm T0 codend would probably improve section for Tiger Flathead, and possibly with minimal impacts on other species.

The remaining zone-4 experiment (phase 2) focused on a T45 mesh panel in an inshore Eastern School Whiting trawl and established no effects of a narrow codend cover on trawl performance (for this species), which has benefits for any future work in this fishery (Appendix 6). Using the cover reiterated the existing minimum SMO of 90 mm is too large for Eastern School Whiting, even when hung at an excessive circumference (to minimize lateral mesh openings), with large numbers of fish ≥17 cm TL (i.e. the suggested minimum commercial size) escaping. A more appropriate T0 mesh size might be ~50 mm SMO, but T45 or T90 mesh at ~47 mm SMO would best match the morphology of 17-cm TL Eastern School Whiting (Broadhurst and Millar, 2023). In the absence of a complete revision of minimum codend mesh sizes for trawlers targeting Eastern School Whiting in NSW state waters, a T45 panel occupying ¼ of the circumference (at the top) of the codend and extending into the lengthener, should improve size section somewhat, although this is simply a temporary solution and ongoing work is required. Such work is being supported by a permit to allow NSW state fish trawlers to trial smaller-meshed T45 mesh panels. Similar panels, but with larger mesh, might have utility for reducing catches of small fish in CTS and GABTS trawls (Appendix 18).

Anterior (zones 2 and 3) modifications: ground gear, separator panels and headline height

The first experiment assessing the utility of anterior trawl modifications in this project was also the first experiment in phase 2, and involved comparing the three most commonly used rubber disc diameters in the centre piece ground gear of CTS and GABTS vessels (i.e. ~90% of the fleet use 4-inch/100-mm, 7-inch/178-mm or 10-inch/254-mm discs) (Appendix 5). The three treatments were chosen for testing based on perceived industry expectations that larger discs would facilitate some small fish escaping under the trawl because of the higher ground-gear line. The collected data contributed to the few previous studies of the effects of ground gears on fish-trawl performance (identified in the international review and more specifically by Engås and Godø, 1989, Brewer et al., 1996; Krag et al., 2010; Larsen et al., 2018). But, while most previous work has shown considerable species-specific variability in performances among similar ground-gear variations (usually due to increases in the fishing height of the ground-gear line off the bottom), none have shown the same null effects as observed here.

The lack of any effects of ground-gear disc diameter on catches in the CTS was attributed to potentially insufficient variation in the ground-gear line height (i.e. only 77 mm between the smallest and largest diameters) to affect the key species, in terms of allowing some to escape under the ground-gear line. Also, while the fished areas, depths and the species encountered were typical of the broader fishery, it is important to acknowledge there might be at least some spatial variation in ground-gear performances. Further, some vessels use smaller discs throughout which would maintain the ground-gear line at the seabed (with no option for fish escape). Other vessels working in deep water use 12 inch/300-mm discs, although compared to the 10-inch ground gear, these would only increase the height of the ground-gear line by ~26 mm. Any future research with ground gears might warrant investigating a greater range of treatments across the CTS, including very narrow disc diameters (i.e. the same size along the entire ground-gear line) and also fishing at various depths (to encounter different species).

Notwithstanding the need for future work, the results support the current approach of not regulating ground-gear disc diameter in the SESSF as a means for affecting selectivity. Ground gears are regulated for trawlers working in NSW state waters. Specifically, southern NSW fish trawlers are limited to a maximum of 100-mm diameter discs in the belief this will preclude access to inshore reefs where large discs allow a ground line to roll over irregular seabed. Nevertheless, access to many ecologically important seabed types off NSW is already restricted via Marine Park closures. By comparison, northern NSW fish trawlers are prohibited from using any rubber discs north of 32°S (i.e. most of the fishery) and instead are restricted to 16-mm chain. This legislation is arbitrary (i.e. no published empirical data) and contrary to any broader objective of limiting seabed impacts, because with intermittently placed large rubber discs between smaller discs, the trawl only contacts the bottom at <10% of the ground-line length, while chains contact at 100% of their length (and at similar or heavier weights). Further work is required to determine any relative differences in catches and/or bottom impacts between chain and rubber-disc ground gears.

The second anterior trawl experiment was also done in the CTS during phase 2 and involved installing a horizontal-separator panel in the aft trawl belly leading to dual (upper and lower) codends to understand size- and/or species-specific vertical orientations in a typical trawl (Appendix 8). This work complemented two previous *in situ* regional studies assessing fish behaviour (Piasente et al., 2004; Yanase et al., 2009), and notwithstanding considerable species-specific variabilities, revealed at least two broad differences that might be used to modify regional trawls.

First, because many commercial fish rise in front of the lengthener, while most non-commercial elasmobranchs remain relatively lower, it might be possible to exclude the latter via modifications to the lower sections of existing trawls, including in the lower body panel or, under some conditions, even bottom-opening grids. Many of the unwanted elasmobranchs during the experiment were larger than the retained species, and their exclusion would dramatically improve trawl selection, which is a priority for some areas in the CTS. Specifically, concern about declines in some elasmobranch populations on trawl fishing grounds off the NSW coast (e.g. Southern Dogfish, *Centrophorus zeehaani* and Harrisson's Dogfish, *C. harrissoni*; Graham et al., 2001) has seen them listed as "conservation dependent" under Australia's Environment Protection and Biodiversity Conservation Act. With the decline mostly attributed to trawling, modifications to reduce catches of unwanted elasmobranchs while still being able to target key species would be beneficial to managing the CTS fishery.

Second, many commercial species, and especially the most abundant, including Tiger Flathead, Silver Trevally, Southern Sawshark, and Eastern Angel Shark mostly entered the lower section of the mid posterior trawl, and so it should be possible to fish at least slightly lower-opening trawls inshore and/or increase mesh size in the upper anterior panels. Because many fish then rise in the posterior trawl, increasing mesh size at this location might also be possible. Doing so would probably not affect species selectivity greatly (and therefore not reduce bycatch), but such modifications, and especially lower headline heights, should reduce drag and therefore fuel usage.

Based on this latter logic, during the final experiment assessing anterior modifications, a conventional CTS trawl with an average headline height of ~3.8 m was alternately fished against a new 'low' trawl with the exact same headline and footrope, but a lower height (mean of ~2.8 m) achieved by removing ~22% of the meshes around the mouth of the trawl and also removing some floats (6%). Catches were not significantly different between trawls, although there were fewer tiger flathead in the low trawl and, regardless of trawl design, significantly lower catches of two batoids (Greenback Stingaree and Smooth Stingray) and greater catches of Velvet Leatherjackets with increasing headline height.

These observations likely reflect subtle variable species-specific responses, and therefore inform behaviour. Specifically, while most species seem to maintain a consistent, relatively low orientation during capture, at least some Tiger Flathead rise up on the trawl mouth. A trawl with a headline height slightly higher than 2.8 m, but lower than 3.8 might warrant testing for utility in maintaining catches of this species. If the headline height reduction is achieved by fewer meshes in circumference at the mouth of the trawl (like for the low design here), then there will be concomitant reductions in drag and therefore fuel.

Regardless of the trawl, the results also imply some effects of varying headline height within designs. One possible explanation for the positive effect of headline height (regardless of trawl type) on the batoids involves changes to ground gear and contact pressure. No monitoring equipment was available for the ground gear, but the fishing line might have changed height relative to the ground gear and increased at higher headlines while decreasing at lower headlines. Also, the pressure of the ground gear on the bottom might have been less at higher headline heights. Possibly some individuals were able to either escape through any larger gap between the rope and ground gear and/or force their way under the ground gear of both trawls as headline heights increased.

The positive effect of headline height on catches of Velvet Leatherjacket is less clear. Like the batoids, this species would be expected to remain on the bottom, although at much smaller sizes and with poor swimming ability, their ability to avoid the trawl might be limited. Many Velvet Leatherjacket were small enough to force their way through meshes at the anterior trawl. Possibly, any changes in the angles of netting panels with changing headline height were sufficient to preclude some escaping at the mouth of the trawl. More data are required to explore these hypotheses, but the data reiterate the dynamic configurations of trawls and how changes to one technical parameter can affect other parameters that potentially explain secondary impacts to species.

Conclusions

The CTS and GABTS face sustainability issues in terms of ecosystem impacts, measured as unwanted fishing mortalities of both the target and non-target species. These mortalities considerably exceed the global average for similar fisheries. The current project sought to improve some of the key issues by (1) reviewing past efforts at improving trawl selectivity via technical changes and proposing a framework for future efforts, before (2) testing existing and new modifications, and finally (3) encouraging the widescale adoption and voluntary exploration of appropriate best-practice technologies. Based on modelling, it is clear satisfying these objectives will have measurable benefits to stocks of key species.

Evidence of achieving the first project objective above is provided in the two reviews, which includes a published framework for ongoing efforts to address problematic environmental inefficiencies. The second objective was clearly satisfied by the various peer-reviewed published papers; the number of which more than doubled and tripled all previous national and south-eastern Australian efforts to date (since the first study in 1993). This new work not only provides a base for ongoing research into improving the selectivity of Australian fish trawls, but also justifies and supports the existing and future efforts of CTS, GABTS and inshore NSW trawlers in terms of trialling new modifications as part of objective 3.

Based on the reviews in objective 1, any future research in these fisheries (and indeed all other Australian trawl fisheries) should follow the defined framework for testing coherent modifications within established, robust experimental designs. Because the discarding rates in each of the manipulative experiments here appear quite high (some were >2× the global average) and legislated codend configurations clearly are not optimal, there remains a need for work to develop more selective designs. The issues are fishery-specific both in terms of problems and solutions, but based on past and ongoing international efforts, such work is likely to realize considerable benefits for improving selection.

Generally, whilst complying with legislative requirements, the selectivities of some GABTS and CTS trawls appear to have been altered such that at some times and locations many small target species are being caught along with high levels of byproduct and bycatch that are ultimately discarded. Although the designs of these trawls have been developed over decades to be regionally specific and suit key targets, marked improvement in trawl selectivity can still be achieved through further minor modifications to the posterior sections. Also, legislation needs to be improved to specify not just minimum codend SMO limits, but also twine diameter, use of double twine and codend circumference so that the intended selectivities of trawls cannot be readily undermined.

While more difficult to control, assess and ultimately legislate, anterior modifications also warrant investigation because in addition to selectivity benefits, these changes can improve efficiencies by reducing drag and fuel. It is evident from overseas research and the work here that various simple anterior-trawl alterations have the potential to cumulatively benefit selectivity. Encouraging these types of investigations within objective 3 through ongoing research is likely to help Australian trawl fisheries minimize discarding to levels commensurate with other developed nations, while at the same time reducing at least some drag and fuel use.

Implications

The project provides empirical data published in the international literature to describe the performance of some industry-developed and new modifications to the trawl bodies and codends of fish-trawls in the CTS and GABTS. In doing so, there is now robust justification (or otherwise) for existing legislated options and for proposed changes in these fisheries, as well as prioritising future efforts to maintain target and by-product catches while minimising unwanted catches (see the next section). The implications of such outcomes are improved environmental viability and a robust base from which scientists and fishers in the CTS and GABTS can direct future efforts towards improving profitability and mitigating the environmental impacts associated with trawling.

Because there is considerable commonality among the general concepts dictating fish-trawl designs, there is the obvious implication for transferring the results of the project to other trawl fisheries around Australia. And any improvements in trawl-gear selectivity have cascading benefits for stocks targeted in interacting fisheries. This means that the beneficiaries of the work are not limited to SESSF fishers. All Australian fish-trawl fisheries and their stakeholders will benefit from lower risk of deleterious trawl impacts, leading to enhanced resource sustainability.

Recommendations

To achieve the stated implications, some substantiated recommendations from the project are to:

- **Maintain unregulated ground-gear disc diameter (within the assessed range).** There currently is no legislation describing ground gear in the SESSF, and this should remain the case (within the tested range of treatments here). But there are legislated ground-gear restrictions for fish trawls used inshore in NSW, and these warrants revision. There is a supposition that larger-disc ground gear will facilitate access to reef, but this can be spatially managed. There is also a need to assess regulations for using chain only in the northern fish-trawl fishery.

- **Consider a minimum size limit for key target species in both fisheries (and not just the CTS).** Like for Tiger Flathead, a minimum size on Deepwater flathead would facilitate defining a more appropriate mesh size in the GABTS.

- **Increase minimum legal T0 mesh size in the GABTS.** At present the CTS and GABTS are managed with the same minimum legal mesh size (90 mm), but the mostly larger-sized key targets in the GABTS warrant a larger minimum T0 mesh size by at least 5 mm, which seems to be the more commonly used size at present.

- **Decrease minimum legal mesh size in the CTS for T90.** If entire codends (with shortened lastridge ropes) or their BRDs in CTS trawls are made of T90 or T45 mesh then a reduction in mesh size (by ~10–15 mm) is warranted, commensurate with twine diameter limitations (single ~3-mm diameter twine).

- **Revise legislated specifications concerning the current T90 and T45 BRD requirements in the GABTS.** Based on the results from work in the GABTS, when made from double twine, the existing legislated BRDs prescribed by AFMA probably have minimal effect on the species or size selectivity of trawls in the GABTS. If a T90 cylinder throughout the anterior codend does not improve size or species selection, it is not realistic to expect a ~90% smaller panel to do anything either.

- **Introduce maximum twine-diameter regulations.** Twine diameter restrictions should be proportional to mesh size throughout the SESSF, starting with 3-mm single twine for 75–80 mm mesh.

- **Address the poor selectivity of inshore NSW fish trawls for Eastern School Whiting via legislated changes to mesh size/shape in codends.** The BRD developed to reduce the bycatch of small Eastern School Whiting could be implemented beyond the existing permit, however other modifications warrant testing. Clearly, the current fish-trawl configurations used in NSW state waters are entirely inappropriate for Eastern School Whiting; a conclusion that is neither surprising nor new, given research over the last 30 years to show that the mesh size is 2× as large as it should be for the largest specimen.

- **Encourage funding agencies like the FRDC to specify a requirement for publishing work to test trawl modifications in international journals.** While the peer-review process is not infallible, requiring the results of experiments to be published in journals will ensure the highest quality of science to support any legislated gear changes.

Further development

Based on the data collected here, future work might include:

- **Investigating modifications to trawls to reduce catches of elasmobranchs.** These taxa accounted for large percentages (30 to 77%) of discards. Some species might be excluded via mechanical separating BRDs, but this will require future commitments in terms of research and operational adjustments to many vessels.

- **Exploring non-technical options to reduce the discarding of fish.** One of the simplest methods for reducing discards (which has accounted for lower rates in some countries) is to develop markets for unwanted species. During the experiments here, Latchet were retained in the CTS, but were regularly discarded in the GABTS. Retaining these latter fish would substantially reduce discarding.

- **Encouraging ongoing industry participation in solutions to ameliorate discarding.** Ultimately, industries should be supported via ongoing dedicated extension activities, and where required, testing of options (like for efforts with penaeid trawlers around Australia).

Extension and adoption

The man outputs from this project were (1) a framework for the ongoing assessment of appropriate modifications to Australian fish trawls, (2) detailed information on the utility of existing and new modifications in the CTS and GABTS; and (3) clear direction for the future development of more environmentally benign trawls for south-eastern and southern Australian fish trawlers. These outputs were extended using existing networks and via the dissemination, extension and adoption plan below.

Extension and adoption plan objectives

1. Encourage the participation of fish trawlers in testing and developing appropriate modifications that improve selectivity for key target species by reducing unwanted bycatch.

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

3. Promote fleet-wide adoption of any recommended modifications.

These objectives were achieved according to the following plan.

(1). Target audience: Commercial fish trawlers and support networks.

> Key message: 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.
>
> Communication/extension: The above key messages were extended during regular port meetings and project steering-committee meetings, and as part of summary reports, expressions of interest and social media during the project (Appendices 14 to 17). Documentation was distributed to individual fishers and other relevant stakeholders though existing social media channels. Fish-trawl fishers in NSW state waters were also given a permit to trial a BRD developed during the project (Appendix 18). Two vessels (one in each of the northern and southern inshore fish-trawl fishery) trialled the BRD as part of their conventional fishing.

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

> Key message: An initial project brief, and then regular non-technical summaries of research results.
>
> Communication/extension: An initial project summary and brief was drafted and web summaries and complete reports of all experimental work were generated to disseminate information from the project to other stakeholder groups and the general public (Appendix 17). Further, all of the experimental work was written up and submitted to international journals as articles. Some of these published articles have open access status and can be downloaded directly from the journal, but all are also freely available on ResearchGate.

(3) Target audience: Fisheries managers.

> Key message: Ongoing outcomes of the research and the recommended implementation of modifications.
>
> Communication/extension: Fisheries managers (from NSW DPI and AFMA) were briefed throughout the project and as part of the committee. All fisheries managers were already well

aware of the need to change trawls to reduce their environmental footprint and so some of the results have already been incorporated into plans for widespread use.

All key messages were disseminated in accord with the milestones for the project. Virtually all results were published and/or disseminated before submission of this final report to the FRDC. The success of the extension plan will be measured by the level of ongoing industry participation and eventual changes to legislation.

Project materials developed

The project materials are detailed in Appendices 3 to 18.

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Appendices

Appendix 1. Intellectual property

The intellectual property is open access. 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:
Matt Broadhurst
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Appendix 3. Knuckey, I., Koopman, M., and Broadhurst, M.K., 2020. Australian fish-trawl fisheries: selectivity and bycatch reduction. Fishwell Consulting. 57 p

Australian fish-trawl fisheries: selectivity and bycatch reduction

Ian Knuckey, Matt Koopman and Matt Broadhurst

Report for FRDC project 2019-27: Improving and promoting fish-trawl selectivity in the Commonwealth Trawl Sector (CTS) and Great Australian Bight Trawl Sector (GABTS) of the Southern and Eastern Shark and Scalefish Fishery (SESSF)

Abstract

The Commonwealth trawl sector (CTS) and Great Australian Bight trawl sector (GABTS) of the Southern and Eastern Scalefish and Shark Fishery (SESSF)—Australia's largest Commonwealth-managed fishery—discard large proportions of their catches (up to twice the global average). In accordance with the Commonwealth Fisheries Bycatch Policy, the fishery is required "*to use a combination of regulatory processes, industry incentives and technological solutions to reduce bycatch and maximise the chance of captured animals surviving*", and "*to draw on best-practice approaches to avoid or minimise all bycatch, and minimise the mortality of bycatch that cannot be avoided*." The present study seeks to facilitate work to address these criteria by critically assessing the utility of existing (from published/unpublished research) and possible modifications (from other fisheries) to trawls to reduce bycatch. We first detail 11 state- and Commonwealth-managed fish-trawl fisheries, including the CTS and GABTS. The characteristics of each fishery, including gear specifications, are listed and, where available, studies undertaken to reduce bycatch are discussed with a detailed focus on the CTS and GABTS. We identified that various simple modifications (involving alternate mesh sizes and shapes) to codends (i.e. aft section of the trawl) have improved selection. Some modifications have been subsequently adopted and legislated. Solutions to reducing capture of unwanted species in trawls have been achieved through extensive collaboration among stakeholders. Nevertheless, despite changes to legislation and regulations arising from the various work done-to-date, bycatch and discarding of unwanted species remains an issue in the CTS and GABTS. Further, the effectiveness of modifications to fishing gear are not clearly evident from initial analyses of logbook or observer data. Although this latter outcome may reflect variability in gear performance throughout the fisheries, we also highlight the possibility of reporting deficiencies. We identify various bycatch issues currently facing the SESSF which, based on efforts in other Australian fisheries and overseas, might be mitigated via further gear modifications, including changes to the forward sections of trawls. Modifying these anterior sections of trawl gear should also improve efficiencies (by reducing drag and fuel). Such improvements would encourage industry adoption of modified fishing gear designed to reduce the capture of unwanted species. With regard to future modifications to trawl gear, priority should be given to changes that mitigate those bycatches of species identified as high risk, protected, or managed under stock-rebuilding strategies.

Introduction

The Southern and Eastern Scalefish and Shark Fishery (SESSF) covers much of Australia's southern coastline and is the major supplier of fresh fish to all adjacent states. The SESSF was formed in 2003 by amalgamating the NSW South East Trawl, Great Australian Bight Trawl, Southern Shark Non-Trawl and South East non-trawl fisheries, and is managed by the Australian Fisheries Management Authority (AFMA). Currently, the SESSF is the largest Commonwealth fishery in terms of volumes caught and in the 2018–19 fishing season the gross value of production (GVP) of the fishery was AU$87 million; accounting for 20% of the GVP of Commonwealth fisheries (Patterson et al. 2020a).

The greatest catches in the SESSF are taken by the various trawl sectors; predominantly the Commonwealth Trawl Sector (CTS) and the Great Australian Bight Trawl Sector (GABTS). Apart from specific sub-fisheries targeting Orange Roughy and Blue Grenadier spawning aggregations, most trawl effort focusses on 'market fishing' for mixed species, and generally has high levels of incidental catches (or 'bycatch'), which can comprise 40–60% by weight of trawled catches.

With respect to catches, the policy framework for Commonwealth fisheries categorises species as either 'key commercial', 'by-product', 'general bycatch' or listed species (endangered, threatened and protected; ETP) under the Environment Protection and Biodiversity Conservation (EPBC) Act, 1999. Key commercial and by-product species are managed in accordance with the Harvest Strategy Policy (DAWR 2018a), while bycatch species are managed via the Commonwealth Fisheries Bycatch Policy (DAWR 2018b) and the EPBC Act, where appropriate. The Bycatch Policy defines bycatch as either those species incidentally taken in a fishery and returned to the sea, or killed or injured as a result of interacting with fishing equipment in the fishery (but not taken). Under the Bycatch Policy, the SESSF is required "*to use a combination of regulatory processes, industry incentives and technological solutions to reduce bycatch and maximise the chance of captured animals surviving*". The policy provides the basis for a transparent and systematic approach to assessing, managing, monitoring and reporting fisheries bycatch in Commonwealth fisheries based on the precautionary principle.

In terms of managing general bycatch, the Commonwealth Bycatch Policy Guidelines (DAWR 2018c) state an objective to "*draw on best-practice approaches to avoid or minimise all bycatch, and minimise the mortality of bycatch that cannot be avoided*". These guidelines recognise bycatch and/or its mortality can be mitigated using several approaches, including: (1) applied technical measures (changes to gear, often including bycatch reduction devices; BRDs); (2) education (to reduce collateral mortalities via improved handling or gear setting); (3) temporal measures (e.g., seasonal closures and day/night setting restrictions); or (4) spatial measures (e.g. depth restrictions or spatial closures—fixed or dynamic).

Notwithstanding the general available options for addressing bycatch and its mortality, by far the most common approach applied nationally, and indeed globally, involves the first option above. Recognition of this characteristic supported the approval of a Fisheries Research and Development Corporation (FRDC) and NSW DPI funded project (2019–027) to investigate the utility of existing and possible future modifications to trawls used in the CTS and GABTS to reduce bycatch, and ultimately improve efficiencies. As a precursor to any applied work in the project, there were requirements to review the relevant (1) domestic and (2) international (Broadhurst and Kennelly, 2021 in Appendix 4) efforts in this area. The current report addresses the first requirement by describing Australian fish-trawl fisheries and summarising the various published/unpublished research into improved selectivity and bycatch reduction as a precursor to prioritising future modifications to be formally assessed for their utility in improving selection among trawls used in the CTS and GABTS.

Methods

Fishery descriptions

Most of the information describing Australian fish-trawl fisheries is contained within state and Commonwealth fishery reports and/or jurisdictional websites. These outputs were reviewed here and a brief description of each fishery is provided, with information on gross value production (GVP), numbers of vessels, catches, target species, minimum gear specifications, and any use of BRDs. The purpose of this section was to compliment efforts by Kennelly and Broadhurst (2021; Appendix 4) and identify any modifications in domestic fisheries that might be relevant to the CTS and GABTS; which are subsequently summarised and discussed.

Efforts at reducing bycatch in south-eastern Australian fish trawls

Following the description of Australian fish-trawl fisheries, we reviewed quantitative attempts at improving selection and or efficiencies in the CTS, GABTS and any related historical state efforts (e.g. NSW inshore fish trawls). Relevant information was obtained by searching completed FRDC projects, Google scholar and Proquest (international peer-reviewed papers), and by emailing relevant researchers and fishers. This information is chronologically presented and critically evaluated.

Analyses of logbook and observer data

Logbook and observer data were obtained for the CTS and GABTS from AFMA. Information relating to seabird mitigation was not analysed because it is outside the scope of this project.

Logbook data were filtered as follows:

- Seabird mitigation devices were removed from BRD fields;
- Duplicate 'shots' (or deployments) were removed;
- Deployments with missing positions were removed;
- Regions were assigned using the spatial function st_join from the R package sf;
- Mesh size (stretched mesh opening; SMO) was rounded to the nearest 10 mm; and
- Catch per unit of effort (CPUE) was calculated using retained weight and deployment duration (hours).

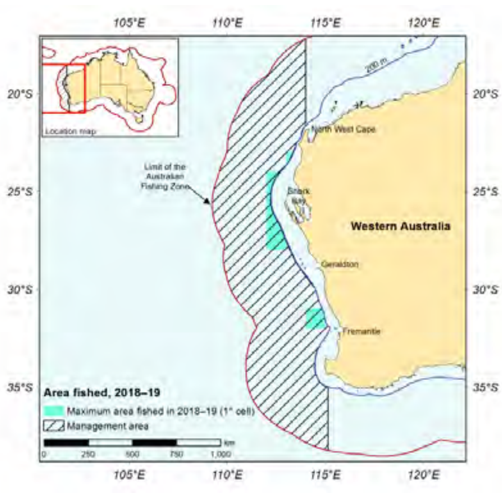
Observer data were filtered as above for the first four criteria, but also very small and very large mesh sizes were removed (assumed errors). Data were used to investigate for any differences in selectivity associated with priority modifications.

Results

Australian fish trawl fisheries

In total, 11 separately managed fish-trawl fisheries were identified. Summaries of these fisheries are detailed below. In these summaries, mesh sizes are either inside stretched mesh opening (SMO; most states and Commonwealth) or for Queensland, centre knot to centre knot (CTC). Turtle excluder devices (TEDs) are a form of bycatch reduction device (BRD).

Commonwealth Western Deepwater Trawl Fishery

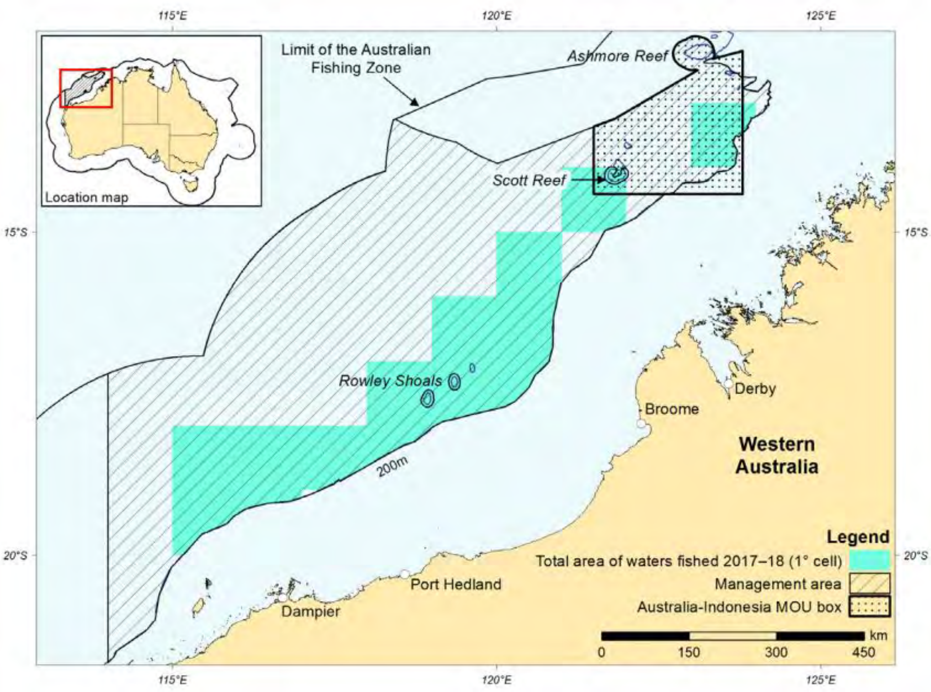


Overview:	Trawls and bycatch/selectivity:

• Catch 100 t, GVP $NA and 11 permits. Gear: • Demersal otter trawl Target species: • Ruby Snapper; and • Deepwater Bugs	• Codend mesh ≥50 mm SMO. Comments: No selectivity or bycatch reduction research relevant to current project.

The Western Deepwater Trawl Fishery operates in waters from about the 2300 m depth contour to the Exclusive Economic Zone (EEZ) from the western boundary of the SESSF to the western boundary of the North West Slope Trawl Fishery. The only restriction on trawls is that the codend SMO must be ≥50 mm (AFMA, 2012). Effort in the fishery remained relatively high during the early 2000s, but has subsequently been low with only 492 trawl hours recorded from one vessel during 2018–19 (Butler and Steven 2020). Catches fluctuated greatly with 378 t landed during 1994–95 and 347 t during 2001–02, but less than 100 t was landed during most other years and only 53 t was landed for 2018–19. An ecological risk assessment found that no species considered high risk were caught by the fishery at current levels of effort (Zhou *et al.,* 2009). No interactions with ETP species were reported in 2019.

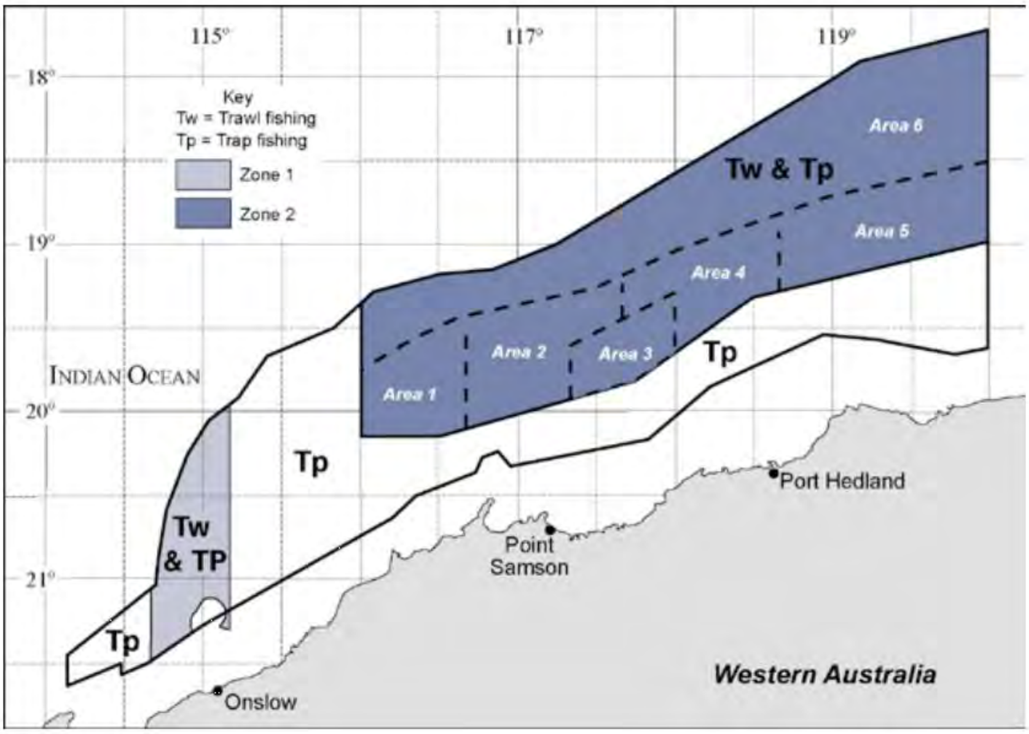
Commonwealth North West Slope Trawl Fishery



Overview: • Catch 80 t, GVP $NA and 11 permits. Gear: • Demersal otter trawl Target species: • Snappers; and • Scampi	Trawls and bycatch/selectivity: • Codend mesh ≥50 mm SMO. Comments: No selectivity or bycatch reduction research relevant to current project.

The North West Slope Trawl Fishery targets Scampi in waters from 200 m depth to the EEZ between 114 and 125°E using demersal otter trawls. The only restriction on trawls is that the codend mesh size must be ≥50 mm SMO (AFMA, 2012). Catches of Scampi reached 175 t during 1988–1989, but have generally been less than 50 t per year since 1994–95. There were four active vessels in the fishery during 2018–19, which completed 2869 trawl hours, landing 67.4 t. An ecological risk assessment found there were no species considered to be at high risk caught by the fishery at current levels of effort (Zhou *et al.*, 2009) and no interactions with ETP species were reported in 2019.

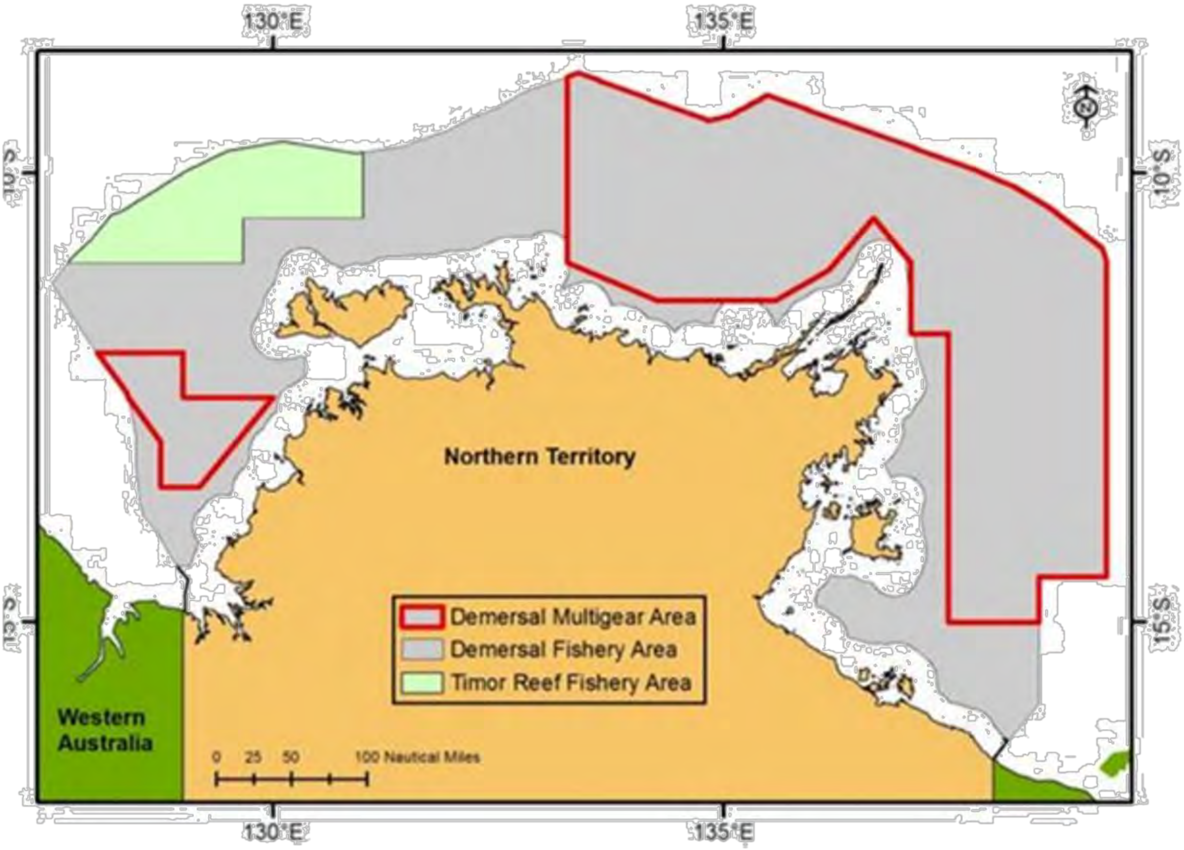
Western Australian Pilbara Fish Trawl (Interim) Managed Fishery



Overview: • Catch ~2000 t, GVP N/A and ~six licences. Gear: • Demersal otter trawl Target species: • Red Emperor; • Rankin Cod; and • Bluespotted Emperor	Trawls and bycatch/selectivity: • Total gear length of <274.3 m; • Mesh size ≥100 mm SMO; and • Bobbins <35 mm diameter. Comments: Some research into BRDs to reduce dolphin captures.

The Western Australian Pilbara Fish Trawl (Interim) Managed Fishery operates in a relatively small area of the shelf between 114 and 120°E, targeting various species (above). Most discarded bycatch species are small bodied and short lived. Given this, and that the fishery covers a very small percentage of the shelf habitat, the impact of the fishery on discarded species is considered to be low (Newman *et al.,* 2020).

Two studies reported the effectiveness of BRDs in reducing catches of ETP species including dolphins, sea snakes, turtles and chondrichthyans (except sawfish) (reviewed by Kennelly and Broadhurst, 2021 in Appendix 4). Bycatch reduction devices are mandatory, effectively reducing the catches of sea snakes and turtles, and there are low levels of interactions with Bottlenose Dolphins (about 5.2 per 1,000 deployments). The risk of the fishery to listed species is reported as low-moderate. In 2018, the fishery reported interactions with 20 dolphins, 45 sawfish, 23 syngnathids and 75 sea snakes.



Overview: 8 licences Gear: • Demersal otter trawl Target species: • Goldband Snapper; and • Red snappers.	Trawl bycatch/selectivity: • Trawl mesh ≥110 mm SMO; • Prohibition on double codend liner; • Footrope weight ≤4kg per m; • Mesh ≤90 ply × 400 denier; • Square-mesh codends; and • TEDs. Comments: The designs of TEDs have been investigated.

The Northern Territory's Demersal Fishery operates from 15 nm offshore to the EEZ, targeting red snappers using semi-demersal otter trawls. In 2016, there were eight active licences (trawl and non-trawl), landing 3478 t of fish (Northern Territory Government, 2018). The mesh must be ≥110 mm SMO and the footrope must not exceed 4 kg per linear m. Turtle excluder devices (TEDs) are mandatory. Square-mesh codends are voluntarily used to minimize bycatch, and improve the value of retained catch. Based on 2016 observer data, bycatches were 24% of the total, with non-retained species comprising mostly trevallies, scads and sharks. During that same year, the fishery recorded interactions with nine sea snakes, 11 turtles, 30 Narrow Sawfish and 55 hammerhead sharks.

The Timor Reef Fishery covers an area of about 8,400 nm^2 to the north west of Darwin. It is a multi-gear fishery targeting deepwater snappers. In 2019, the fishery landed 941 t comprising mostly red snappers and Goldband Snapper. Trawl bycatch was estimated to be ~28% of the total based on a 2015 observer program. The main discarded species were sharks, tropical snappers, triggerfish, scads, Black Tripodfish, Common Saury and Largehead Hairtail. Interactions with ETP species include sea snakes, sawfish, Whale Shark, hammerhead sharks, groupers and the Australian Butterfly Ray.

Overview: • Catch ~500 t, GVP N/A, and two licences. Gear: • Demersal otter trawl Target species: • Tropical snappers; and Crimson and Saddletail snappers.	Trawls and bycatch/selectivity: • Wing and belly sections not exceeding 300 mm (CTC) with a diameter of not more than 4 mm; Maximum ground-gear weight; • Codend mesh size of ≥110 mm; • Mandatory BRDS (including TED); and • Weight on the footrope not exceeding 4 kg per m. Comments: Quantitative data on BRDs is required.

This fishery (GOCDFFTF) is managed by QDAF under the Queensland *Fisheries Act* 1994, Queensland Fisheries (Commercial Fisheries) Regulation 2019 and the Fisheries (General) Regulation 2019. The fishery has operated under Queensland Fisheries Joint Authority (QFJA) jurisdiction since June 1998. The QFJA was established via an arrangement between the Commonwealth and Queensland which, among other things, states that the relevant species be managed by the QFJA under Queensland law. Fishers in the GOCDFFTF are permitted to use a semi-demersal otter trawl. All trawls must have BRDs (including a TED) installed, which need to excluding fish <35 cm total length (TL) and all "species of conservation interest" (QDAF, 2020). The codend must have a mesh size ≥110 mm centre-knot-to-centre-knot; CTC); but the anterior section requires a mesh <300 mm CTC. The twine diameter must be <4 mm, and the codend uncovered other than within 1.5 m of its drawstring. The weight on the footrope (including bobbin lines, chains, bridles and any other device weighing on the footrope) must not exceed 4 kg wet weight in the air per m.

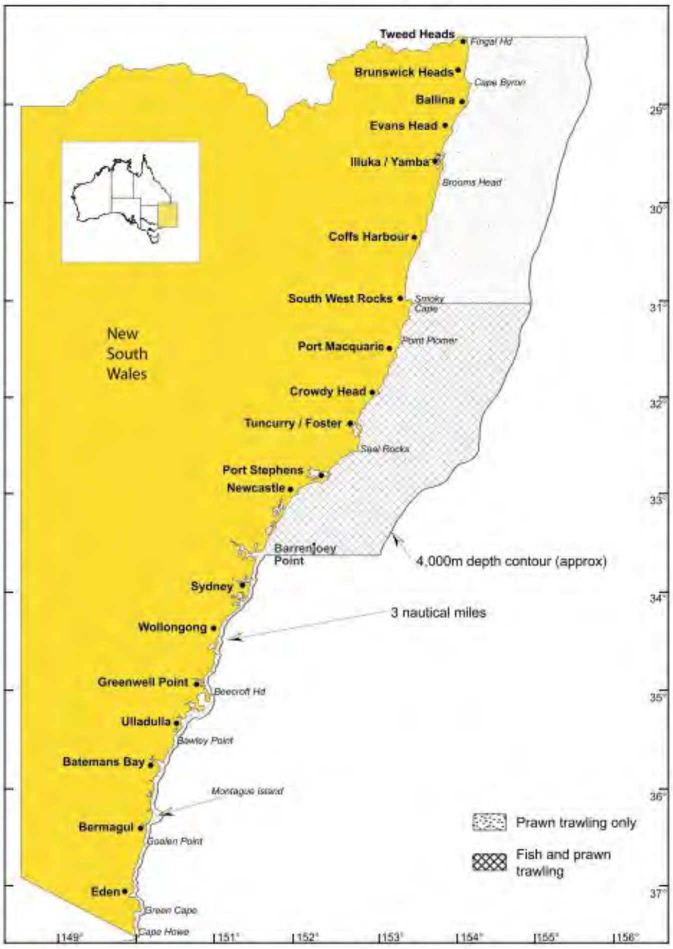
Catches in the GOCDFFTF ranged from 532 t during 2011 to 17 t during 2016, but there has not been any fishing since 2016. The main species landed were Crimson and Saddletail snappers. Since the introduction of BRDs (including TEDs), no interactions with ETP species have been reported. However, anecdotal information prior to logbooks, and data from a discontinued observer program reveal that the fishery previously interacted with Olive Ridley and Flatback turtles, Elegant Sea Snake, pipefishes, Narrow Sawfish, Queensland Groper, Barramundi Cods, Scalloped Hammerheads, Great Hammerheads, and Leopard Sharks.

Queensland Fin Fish (Stout Whiting) Trawl Fishery

Overview: Catch ~1000 t, GVP $2.1 m and two active licences. Gear: • Scottish seine; and • Demersal otter trawl. Target species: • Stout Whiting; with Yellowtail Scad and Goatfish by-product	Trawls and bycatch/selectivity: • ≥38 mesh ≤100 mm CTC; • Net length ≤80 m, otter-trawl sweeps ≤128 m; and • Mandatory TEDs in otter trawls. Comments: None.

The Queensland Fin Fish (Stout Whiting) Trawl Fishery targets Stout Whiting from Bundaberg to the Queensland/NSW border. There were only two active licences during 2017, collectively fishing for 246 days, and landing 1028 t (DAF, 2019). Data from an observer program undertaken during 2009–10 revealed discard rates of 39–49% of the otter-trawl catch and 24–51% of the Scottish-seine (incorrectly termed 'Danish seining') catch. Much of this bycatch comprised sharks and rays, including the Eastern Shovelnose Ray, Bluespotted Mask Ray, Common Stingaree, guitarfishes and weasel sharks. Bycatch has been reduced via legislated TEDs in the trawls. Listed bycatch species include sea snakes and pipehorses. Otter trawls and Scottish seines are required to be no longer than 88 m and have mesh sizes of at least 38 mm CTC. Otter trawls must have sweeps <128 m, whereas the haul ropes of Scottish seines must not exceed 2500 m.

NSW Ocean Trawl Fishery

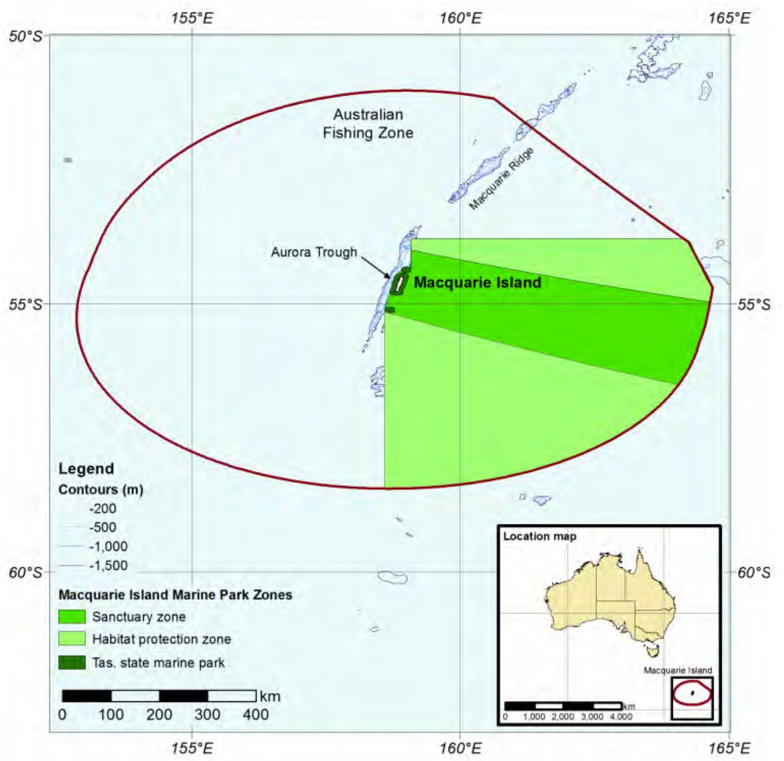


Overview: Catch ~1000 t, GVP $2.1 m and 43 active licences between northern and southern sectors. Gear: • Demersal otter trawl. Target species: • Various, but including whiting; • Silver Trevally; and flatheads.	Trawls and bycatch/selectivity: • Mesh size ≥90 mm SMO; • Single twine no more than 6 mm diameter; • Codend twine can be double twine of not more than 5 mm diameter on whiting grounds; • Sweeps no more than 274 m; • Total length of net 60 m maximum; • No more than one ground chain with links no more than 16 mm diameter; and • Rubber discs not exceeding 100 mm diameter south of 32° 30'S (no discs north of this latitude). Comments: No work with fish-trawl BRDs has been done.

The NSW Ocean Trawl Fishery includes all waters north of Barrenjoey Headland seaward to the 4000-m depth contour (northern zone), and waters south of Barrenjoey Headland seaward to the 3-nm line (5.6 km) (southern zone). All vessels use otter trawls, although one vessel also deploys a Scottish seine. There are 26 endorsement holders in the northern zone, and 17 in the southern zone (DPI, 2017). The fishery landed ~1000 t during 2015–16. Listed species interacted with the fishery include the Great Hammerhead, Scalloped Hammerhead and New Zealand Fur Seal.

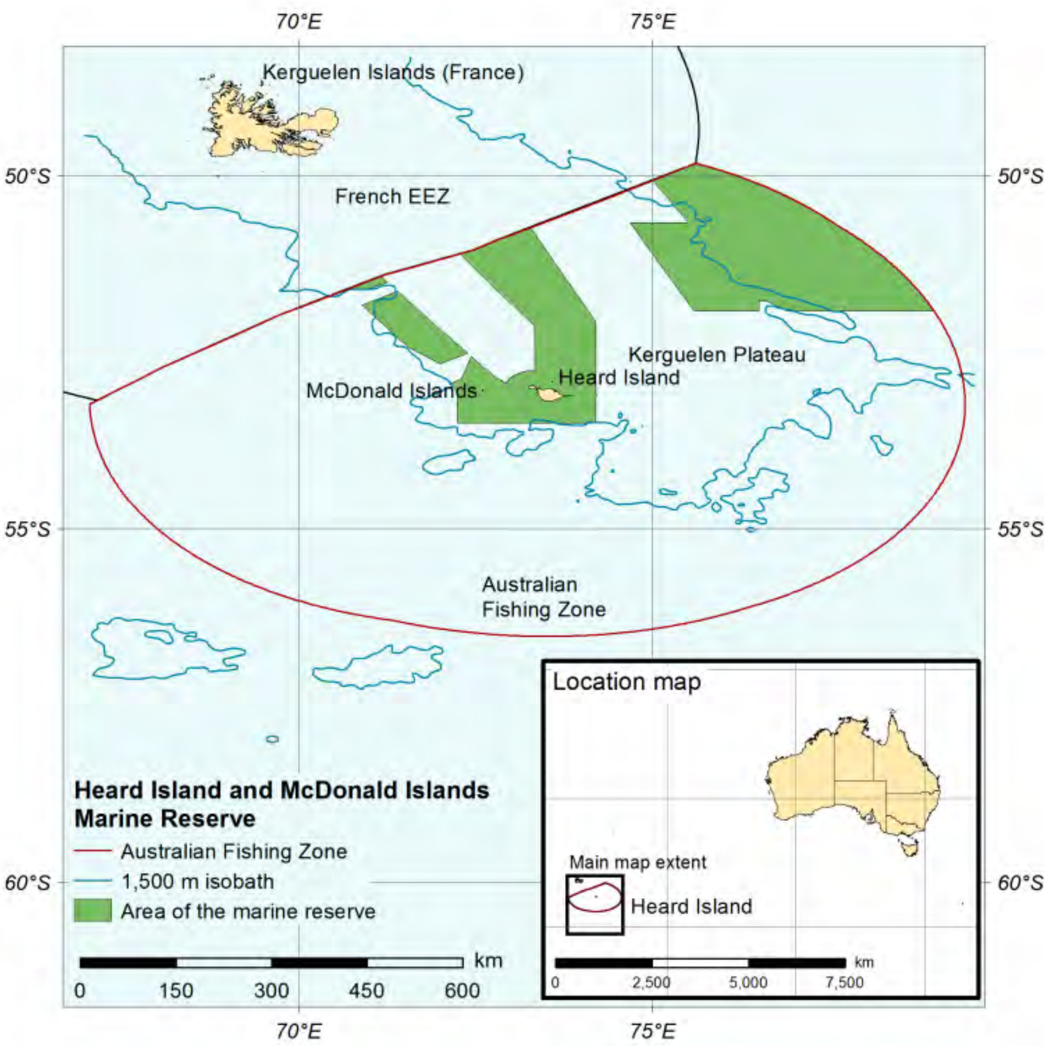
The mesh size must ≥90 mm SMO diameter single twine. However, double twine (up to 5 mm diameter) may be used in codends on whiting grounds. Bobbin ground gear (i.e. rubber discs) is prohibited north of 32° 30' S (northern zone) and although these are permitted southwards, they must be ≤100 mm diameter. Sweeps can be no longer than 274 m and the maximum length of the net is 60 m. Only one ground chain can be used with a maximum link diameter of 16 mm. BRDs are not required by fish trawlers working in inshore NSW waters.

Commonwealth Macquarie Island Fishery



Overview: • Catch ~450 t, GVP $N/A and two licenses. Gear: • Demersal otter board trawl; but typically • longline. Target species: • Mackerel Icefish; and • Patagonian Toothfish.	Trawls and bycatch/selectivity: • Mesh size ≥120 mm SMO for toothfish; • Bobbin gear ≥520 mm; and • Rockhopper disc ≥400 mm. Comments: No relevant selectivity or bycatch reduction research relevant to the current project.

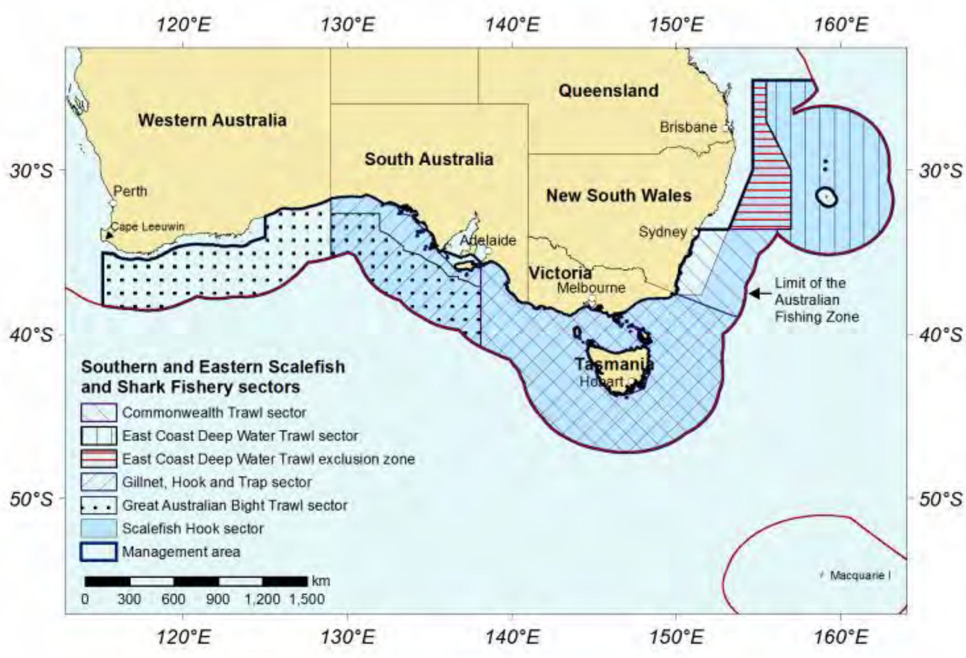
The Macquarie Island Fishery targets Patagonian Toothfish with otter trawls and demersal longlines from 3 nm offshore from Macquarie Island to the EEZ. However, otter trawls have not been used in the fishery since 2010–11. There are only two quota (statutory fishing right) holders and one active vessel during 2019–20 (Patterson and Steven, 2020). During the 2019–20 fishing season, 451 t of Patagonian Toothfish was landed from 81-longline days. Trawls must have a SMO ≥120 mm throughout, bobbins at least 520 mm in diameter and rock hopper rubber discs at least 400 mm in diameter. During 2019, 27 interactions with Porbeagle Sharks and three with Antarctic Sleeper Sharks were recorded. However, these were caught with longlines.



Overview: • Catch ~3400 t, GVP $NA and four licenses. Gear: • Demersal otter trawl; but now mainly • longline. Target species: • Mackerel Icefish; and • Patagonian Toothfish.	Trawls and bycatch/selectivity: • Mesh size ≥120 mm SMO for Patagonian Toothfish; and • ≥90 mm SMO for Mackerel Icefish. Comments: No selectivity or bycatch reduction research relevant to current project.

The Heard Is and McDonald Is Fishery operates from 13 nm offshore from the islands to the extent of the Australian EEZ. The fishery targets the Patagonian Toothfish and Mackerel Icefish using demersal longlines, and otter trawls, midwater otter trawls and pots (fish traps). During the 2018–19 fishing season, there were five active vessels that landed 3,390 t of Patagonian Toothfish and 443 t of Mackerel Icefish from 64 trawl days and 17,745,965 hooks set. Trawls must have a mesh size ≥120 mm SMO throughout for Patagonian Toothfish, and 90 mm SMO for Mackerel Icefish (Sporcic *et al*., 2018). Bobbins must be at least 520 mm in diameter and rock hopper rubber discs must be at least 400 mm in diameter. The main bycatch species include Unicorn Icefish, Grey Rockcod and various skates and rays. During 2019, the fishery reported catches of one each of a Porbeagle Shark and Antarctic Sleeper Shark.

Commonwealth Southern and Eastern Scalefish and Shark Fishery (SESSF)



The SESSF comprises three separate trawl sectors. All are subjected to the same gear restrictions, but with some divergence on operation. These differences are reiterated in the boxes below.

<u>*Commonwealth Trawl Sector*</u>

Overview:
• Catch ~30,000 t, GVP \$42 m, and 52 vessels.
Gear:
• Otter board trawl (32 vessels); and
• Scottish seine (20 vessels).
Target species:
• Multi-species, but especially Tiger Flathead, Ling, Blue Grenadier, and Orange Roughy.
	Trawl bycatch/selectivity
	• When fishing for prawns ≥40 mm codend and ≤60 mm SMO.
	• When targeting fish:
	  • wings and net mouth (shoulders, belly and veranda) ≥115 mm SMO.
	  • Codend:
	    • ≥90 mm SMO single twine mesh; or
	    • ≥102 mm SMO double twine; or
	    • ≥90 mm SMO double twine mesh + BRD, comprising:
	    • Single square mesh (≥90 mm SMO) panel in upper side of codend bag (minimum 15 × 20 bars); or
	    • Single rotated (T90) mesh (≥ 90 mm) panel in upper side of codend bag (minimum 15 × 18 meshes).
	
	Comments
	• Seabird bycatch alleviated;
	• Seals are an ongoing issue;
	• Rare catches of dolphins;
	• Skates and rays are issues;
	• Gulper sharks are an issue (Royal Red Prawn fishery);
	• General reduction of small-fish bycatch; and
	• Lower benthic impacts (footprint has reduced).

The Commonwealth Trawl Sector (CTS) extends from Barrenjoey Point (NSW; outside 3 nm), south around Victoria and Tasmania to Kangaroo Island (SA) and out to the EEZ. Demersal otter trawls and Scottish seines are mostly used, but pair trawling and midwater trawling methods are also permitted. There were 30 active trawl vessels and 19 active Scottish seiners recorded during the 2019–20 fishing season (Emery *et al*., 2020). During that season, the fleet landed 12,346 t of quota species comprising mostly Blue Grenadier, Tiger Flathead, Pink Ling and eastern-zone Orange Roughy. Gear specifications vary across sub-sectors.

The mesh size of Scottish seine nets must not be less than 38 mm SMO in any part when targeting Eastern School Whiting, and 75 mm SMO when targeting flathead. When targeting Royal Red Prawns, a mesh size must not be less than 40 mm or greater than 60 mm SMO in any part. Other demersal otter trawls must have wing and mouth mesh sizes not less than 115 mm and codend mesh sizes of not less than 90 mm single twine, 102 mm double twine or 90 mm double mesh when combined with one or more of the following BRDs:

- a single large square-mesh (of at least 90 mm) panel in the upper side of the codend (of minimum dimensions 15 × 20 bars); or
- a single large rotated mesh (of at least 90 mm) panel (called a T90) in the upper side of the codend (of minimum dimensions 15 × 18 meshes).

Estimated discards during 2011 comprised about 2000 and 10,000 t of quota and non-quota species respectively (Tuck *et al*., 2013). The bycatch in the CTS is mostly small fish with little or no commercial value. However, some quota species, together with sharks and rays are also discarded. The main non-quota species discarded are Barracouta, whiptails, New Zealand Dory, gurnards, Frostfish and Common Jack Mackerel. Discarding of quota species varies more depending on recruitment, market demand and quota availability, with the main species discarded being Redfish, Silver Warehou, Blue Grenadier, Tiger Flathead, Mirror Dory, Orange Roughy, Reef Ocean Perch, Bigeye Ocean Perch and Jackass Morwong. The fishery interacts with listed species including, marine mammals, seabirds, sharks and syngnathids. During 2019–20, interactions were reported with Albatrosses, Australian Fur Seal, New Zealand Fur Seal, Porbeagle Shark, Shortfin Mako, Common Dolphin, White Chinned Petrel, seahorses and pipefishes, Buller's Albatross, Shy Albatross and Shearwaters.

Great Australian Bight Trawl Sector

Overview:
• Catch ~1500 t, GVP $9 m and four vessels (11 permits).
Gear:
• Otter board trawl (three vessels); and
• Scottish seine (one vessel)
Target species:
• Bight Redfish; and
• Deepwater Flathead
	Trawl bycatch/selectivity:
	• Wings and net mouth ≥115 mm SMO;
	• Codend:
	  • mesh ≥90 mm SMO single twine;
	  • ≥102 mm SMO double twine; or
	  • mesh ≥90 mm SMO double twine with at least one BRD:
	    • single square mesh (≥ 90 mm) panel in upper side of codend bag (minimum 15 × 20 bars); or
	    • single rotated (T90) mesh (≥90 mm SMO) panel in upper side of codend bag (minimum 15 × 18 meshes).
	  • Industry typically uses ≥94 mm; and
	• Code of conduct suggests using a T90 extension.
	
	Comments
	• Bycatches often comprise skates and rays; and small individuals of target species.

The Great Australian Bight Trawl Sector (GABTS) extends from the western boundary of the CTS to 115°E, with fishing occurring on the shelf and the slope. Both demersal otter trawl and Scottish seines are used, with three and one vessels, respectively recorded fishing during 2019–20. These vessels landed 1,600 t of fish in that year, from 13,910 otter-trawl hours and 3212 Scottish-seine deployments. The main target species are Bight Redfish and Deepwater Flathead. Trawl specifications are the same as for the CTS, although a code of conduct suggests using a T90 (typically ~94 mm SMO) extension among the few GABTS vessels.

During 2005–2014, about 56% of the GABTS catch was discarded, with an average of 2,311 t discarded over previous years (Koopman, *et al*. 2017). The main discarded fish species during that time were Latchet, Wide Stingaree, Ocean Jacket, Stingarees, Giant Stingarees and Barracouta. There is very little discarding of quota species. Sponges also can contribute to discards. No interactions with listed species were recorded during 2019–20. However, interactions with Flesh Footed Shearwater, and Pipehorses have been previously reported (Tuck *et al*., 2013).

East Coast Deepwater Trawl

<table>
<tr>
<td>Overview:
Catch ~0–400 t, $GVP NA, and one vessel
Gear:
Demersal and midwater trawl
Target species:
Alfonsino</td>
<td>Trawl bycatch/selectivity:
Midwater trawl ≥90 mm SMO
Demersal trawl when fishing for prawns ≥40 mm codend and ≤60 mm SMO
Demersal trawl when targeting fish: wings and net mouth ≥115 mm SMO;
Codend:
mesh ≥90 mm SMO single twine;
≥102 mm SMO double twine; or
mesh ≥90 mm SMO double twine with at least one BRD:
Single square mesh (≥ 90 mm) panel in upper side of codend bag (minimum 15 × 20 bars); or
Single rotated (T90) mesh (≥90 mm SMO) panel in upper side of codend bag (minimum 15 × 18 meshes).
Pair trawling: Mesh ≥90 mm SMO
Comments: Catch and effort are very low, with no effort during 2018–20; but reported interactions with dolphins, sea lions, and seals.</td>
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The East Coast Deepwater Trawl Sector operates sporadically, targeting Alfonsino around the Lord Howe Rise. Permitted fishing methods are midwater and demersal otter trawl, Scottish seine and pair trawls. The same trawl restrictions apply as for the CTS and GABTS. As much as 400 t of Alfonsino has been caught during a fishing season. However, catches have been very low since 2007–08, and there has been no fishing since 2017–18 (Georgeson and Curtotti, 2020).

Efforts at reducing bycatch in south-eastern Australian fish trawls

Over the past 25 years, there have numerous research programs (mostly FRDC-funded) aimed at improving selectivity in fish trawls used off south-eastern and southern Australia: mostly in the CTS and GABTS. These studies and their key findings are chronologically listed below.

FRDC project 93/180: Development of by-catch reducing prawn-trawls and fishing practices in NSW's prawn-trawl fisheries (and incorporating an assessment of the effect of increasing mesh size in fish trawl gear)

In one of the earliest studies off Newcastle and Bermagui, including in what is now the CTS, Broadhurst and Kennelly (1995) compared the catches of fish from a conventional fish trawl (constructed of 90 mm SMO mesh in the body and codend) with those from a fish trawl constructed of 100 mm mesh in the body and codend. Compared with the conventional trawl, the larger-meshed design trawl retained 27% less bycatch, but also 28% fewer Tiger Flathead.

The 100-mm trawl also reduced the numbers and weights of discarded Tiger Flathead by 48 and 47%, respectively and the numbers and weights of discarded Rubberlip Morwong by 57 and 63% respectively. However, for John Dory, at a particular location where large numbers were encountered, the 100-mm trawl caught significantly more fish than the conventional trawl (a mean increase in weight of 66%). The study revealed a need to determine species-specific mesh selectivities, and to assess the behaviour of fish in trawls.

Although increasing mesh size produced positive results, an important caveat with this work is that no net-monitoring gear was used. Therefore catches could not be standardized for probable differences in swept area. This shortfall limits some interpretation of the data. Overseas work has clearly demonstrated that such net monitoring gear must be used when assessing anterior-trawl modifications (Kennelly and Broadhurst, 2021; Appendix 4).

FRDC Project 1998/204: Effects of Trawling Subprogram: Maximising yields and reducing discards in the South East Trawl Fishery through gear development and evaluation.

Following the success of bycatch reduction work with prawn trawls off eastern Australia and overseas, Knuckey and Ashby (2010) undertook trials of gear modifications to: (1) reduce discards in the east (e.g. Bermagui) and west (Portland) of the CTS; (2) assess the degree to which any discard reductions would meet targets; (3) quantify the economic implications of gear modifications; and (4) develop an extension strategy to communicate results to stakeholders. They undertook covered-codend experiments to determine the selectivity of standard (control) 90-mm SMO diamond-mesh codends, made *in situ* observations of the behaviour of commercially important fish species using underwater cameras, compared codends constructed of different mesh sizes and/or shapes (90-mm square, 102-mm diamond/square, 110-mm diamond/square) to a standard (control) 90-mm diamond-mesh codend using trouser-trawl experiments, and modelled the impact of adopting modified codends with respect to stock biomass, retained yield, catch value and discard levels.

The results of the covered-codend experiments revealed that about 70% of organisms (30%) by weight passed through the codend and were caught in the cover, comprising mostly small fish (96% by weight). The main species caught in the cover were Toothed Whiptail, Grey Whiptail, Threespine Cardinalfish and Blacktip Cucumberfish. Quota species only comprised 7% of the weight of fish caught in the cover, including Ocean Perch, Eastern Gemfish, flatheads, Pink Ling and Redfish.

The study found that all treatment codends reduced the discards of non-commercial species in deep water off Bermagui, and catches of commercial discards were reduced in the 90-mm square and 102-mm diamond codends (Figure 1). Most test codends also caught fewer commercially retained fish at this site, except for the 90-mm square codend for which there was no significant difference in weights of catches. The treatment codends reduced catches of the discard species Blacktip Cucumberfish, Grey Whiptail, Threespine Cardinalfish and Toothed Whiptail in deep water off Bermagui, while the 102-mm square and 110-mm diamond codends also greatly reduced catches of other discard species including Armoured Gurnard, Common Sawbelly and Spiny Flathead.

The effects on catches of individual species differed among gears. The 90-mm square-mesh codend made little difference to catches of most commercial species except for reducing the numbers of retained Pink Ling and discarded Offshore Ocean Perch. The 102-mm diamond-mesh codend reduced retained catches of the commercially important Mirror Dory, Pink Ling and Gould's Squid, while also reducing catches of discarded Offshore Ocean Perch. The retained catches of Pink Ling and Offshore Ocean Perch were lower in both the 102-mm square-mesh and 110-mm diamond-mesh codends, and the latter also retained fewer

Gould's Squid. Those two mesh configurations similarly reduced the discarded catches of Offshore Ocean Perch, but increased catches of discarded Mirror Dory.

The reductions in the catches of retained and discarded commercial species by the 102-mm square-mesh codend were similar to those of the 90-mm square-mesh codend, except it also caught fewer retained Gould's Squid and slightly more Silver Trevally than the control. The 110-mm diamond-mesh codend caught fewer retained cuttlefish, Gould's Squid, Inshore Ocean Perch, octopus, Redfish, Silver Trevally and Tiger Flathead, as well as discarded Inshore Ocean Perch, Redfish and Tiger Flathead.

The 90-mm square-mesh codend had no significant effects on catches of any of the three groups of species in shallow water off Bermagui, other than reducing the number of non-commercial discard fish caught (Figure 2). All other treatment codends significantly reduced the weights and numbers of non-commercial discards and commercial discards, and also the numbers of commercially retained fish. There were no significant differences between the weights of commercially retained species caught using 102-mm diamond- and square-mesh codends. In shallow water off Bermagui, the 90-mm square-mesh codend caught fewer retained and discarded Tiger Flathead and retained Velvet Leatherjacket, but more retained and discarded Redfish. The 102-mm diamond-mesh codend caught fewer retained and discarded Redfish and Tiger Flathead, retained Silver Trevally and Velvet Leatherjacket and discarded Inshore Ocean Perch. All test codends in shallow water off Bermagui caught fewer Round Snouted Gurnard than the control codend. The 102-mm diamond-and square-mesh and 110-mm diamond-mesh codends also caught much fewer Blacktip Cucumberfish and Grooved Gurnard than the control codend. The 110-mm diamond-mesh codend also caught fewer Common Bellowsfish.

The 102-mm diamond-mesh codend reduced catches of all groups, except the weight of commercial retained species in deep water trials off Portland (Figure 3). The 102-mm square- and 110-mm diamond-mesh codends both significantly reduced the numbers of non-commercial discard fish, but made little difference to the weights and numbers of other species groups. A significant reduction in the catch of non-commercial discarded species occurred in the 110-mm square-mesh codend, with no reduction in catches of commercially retained species. All treatment codends caught fewer Blacktip Cucumberfish and Toothed Whiptail in deepwater of Portland, with the 110-mm square-mesh codend nearly eliminating catches of Blacktip Cucumberfish. Catches of Grey Whiptail were reduced by both the 110-mm square-mesh codend and 102-mm codends, while the numbers of Banded Bellowsfish were also greatly reduced in catches using the 110-mm square-mesh codend.

Most modified codends made very little difference to the catches of Blue Grenadier in deepwater off Portland, except for the 110-mm diamond-mesh codend which retained fewer discarded Blue Grenadier compared with the control net. Compared with the control, the 102-mm square-mesh codend also caught fewer discarded Blue Grenadier. Similarly, compared with the control, the 110-mm square-mesh codend caught fewer retained and discarded Gemfish and retained Offshore Ocean Perch and Gould's Squid. The 102-mm diamond-mesh codend caught considerably fewer Greeneye Dogfish.

Overall, the results of sea trials in shallow water off Portland were almost identical to those in deep water. The 102-mm diamond-mesh codend caught fewer non-commercial discard species, but a similar weight of commercially retained species as the control codend (Figure 4). The 102-mm square- and 110-mm diamond-mesh codends had few effects on catches other than the latter catching a significantly lower number of non-commercial discard species. Reduced catches of non-commercial discard species were observed in the 110-mm square-mesh codend, unlike in the deepwater trials, this test codend also significantly reduced the catches of commercially retained fish. In shallow water off Portland, fewer New Zealand Dory, Blacktip Cucumberfish and Southern Whiptail) were caught by the 102-mm diamond-mesh codend, while the 102-mm square-mesh codend reduced catches of a greater variety of species including Blacktip Cucumberfish, Jack Mackerel, Bigscale Rubyfish and Southern Whiptail. Using the 110-mm square-mesh codend resulted in reduced catches of Thetis Fish, Toothed Whiptail, Draughtboard Shark, and New Zealand Dory, while Bigscale Rubyfish, Blacktip Cucumberfish and Jack Mackerel were all nearly totally excluded from the catch.

Modelling undertaken by Knuckey and Ashby (2010) revealed that in all cases tested, adopting any of the modified codends in the fisheries would significantly reduce discards, but would come at the cost of an initial decrease in yield and value of total catches ranging between 5–15% depending on the region and codend. Those losses reduced over time and compared with the 90-mm diamond-mesh codend, positive returns were generally achieved after 4–6 years. Long-term improvements in yield and catch were around 5%, but varied considerably for different species, whereas some species such as Gould's Squid did not regain a positive yield. The 110-mm diamond-mesh codend resulted in the greatest increase in yield off Bermagui, whereas the 110-mm diamond and 102-mm square-mesh codends performed best off Portland. Only the 110-mm square codend resulted in a long-term decrease in catch value.

Given the economic situation in the fishery at the time results were released, it was anticipated that there would be significant resistance to uptake of trialled codends. This prompted the FRDC to fund a project entitled "Promoting industry uptake of gear modifications to reduce bycatch in the South East Trawl Fishery (FRDC Project 2001/006)" (below). Through this project and ongoing work by SETFIA, larger and/or rotated-mesh panels were introduced into several trawls in the SESSF and were ultimately mandated in December 2005 (Table 1).

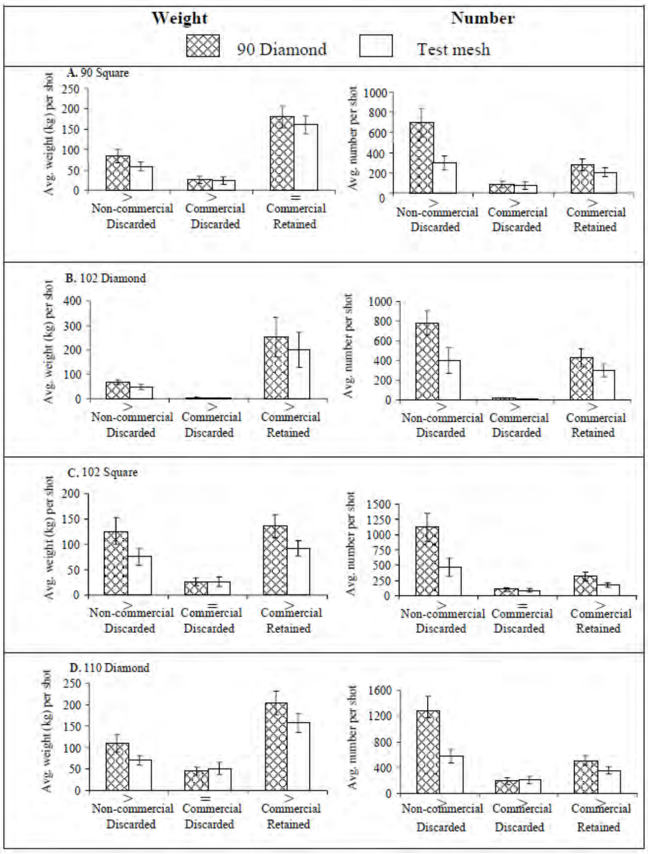


Figure 1. Average weight (left column) and number (right column) per deployment of commercial and non-commercial fish discarded and retained from deep water (>150 fth) off Bermagui (east). The test mesh was: A, 90 mm square; B, 102 mm diamond; C, 102 mm square; and D, 110 mm diamond. Error bars ±SE. Symbols > and< denote significant differences and the direction of that difference; = denotes no significant difference.

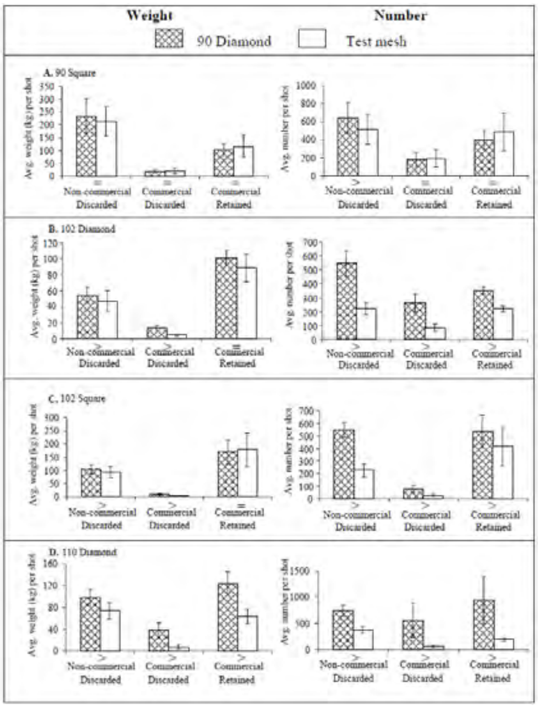


Figure 2. Average weight (left column) and number (right column) per deployment of commercial and non-commercial fish discarded and retained from shallow water (<150 fathoms) off Bermagui (east). The test mesh is: A, 90-mm square; B, 102-mm diamond; C, 102-mm square; and D, 110-mm diamond. Error bars ±SE. Symbols > and< denote significant differences and the direction of that difference; = denotes no significant difference.

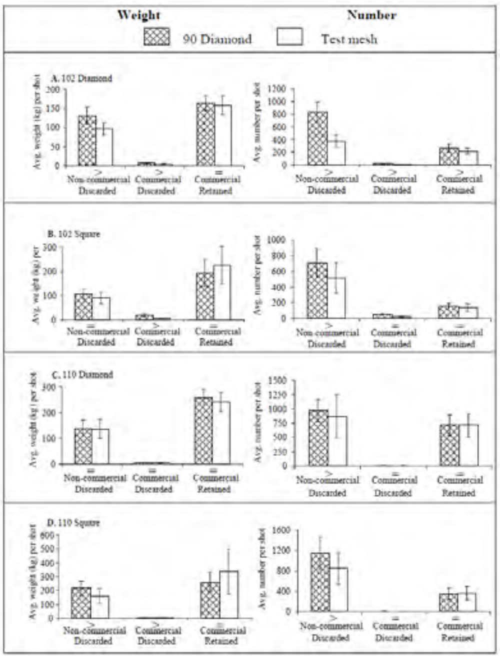


Figure 3. Average weight (left column) and number (right column) per deployment of commercial and non-commercial fish discarded and retained from deep water (>150 fathoms) off Portland (west). The test mesh is: A, 102-mm diamond; B, 102-mm square; C, 110-mm diamond; and D, 110-mm square. Error bars ±SE. Symbols > and< denote significant differences and the direction of that difference; = denotes no significant difference.

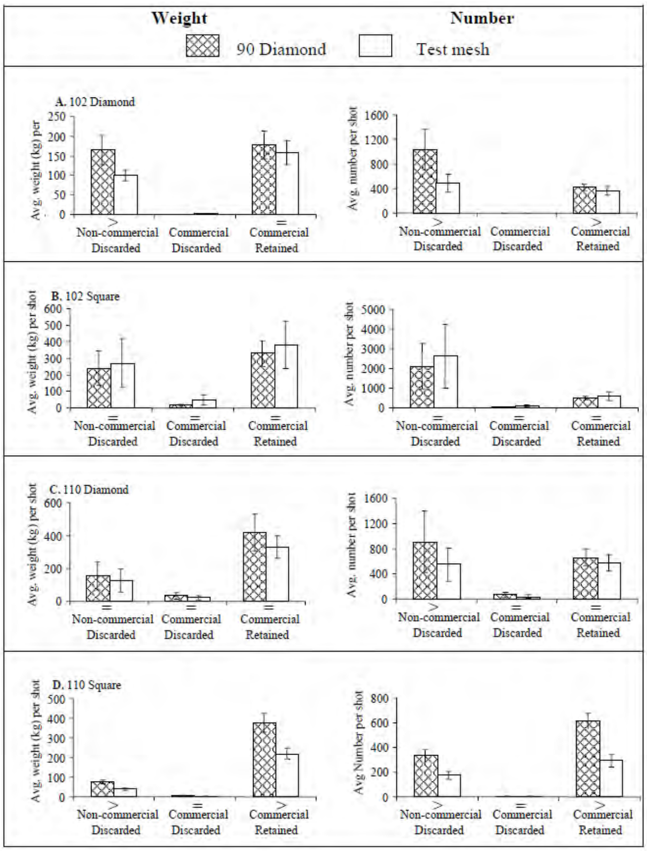


Figure 4. Average weight (left column) and number (right column) per deployment of commercial and non-commercial fish discarded and retained from shallow water (<150 fathoms) off Portland (west). The test mesh is: A, 102-mm diamond; B, 102-mm square; C, 110-mm diamond; and D, 110-mm square. Error bars ±SE. Symbols > and< denote significant differences and the direction of that difference; = denotes no significant difference.

FRDC Project 2001/006: Promoting industry uptake of gear modifications to reduce bycatch

This project was done by Walker *et al.* (2010) to facilitate the uptake of gears trialled in the earlier FRDC Project 1998/204. The project had the following aims:

1. Through application in normal fishing practices, industry improve the initial gear modifications (from FRDC Project 1998/204) to retain commercial species and reduce bycatch and discarding.
2. Promote voluntary uptake of modified gear by a large percentage of commercial fishers in the South East Trawl Fishery.
3. Allow fishers to observe fish behaviour, trial, modify and improve the gear over a 12-month period assisted by underwater video equipment.
4. Review alterations that fishers have made and scientifically test the performance of the modified gear and review changes to fish behaviour within the gear.
5. Compare the catch and catch composition between two trawl codend constructed of 90-mm diamond mesh netting where one is fitted with a 'T90 selector panel' and the other is not through sea trials using a demersal trouser-trawl rig.

The project was undertaken through four operational components, including fish behavioural studies; extension; trials of modified codends by industry; and experimental sea trials of a T90 selector panel in codends. The fish behavioural studies analysed and documented underwater footage from inside trawls. The amount of escape by commercial species by swimming through the meshes in the wings, body and codend of the trawl net, or by swimming out of the path or out of the main opening of the trawl nets was also quantified. These results are documented in FRDC Project 1998/204, and video tapes of fish swimming in trawl nets were widely distributed to industry and other stakeholders during the extension component of the project.

Extension involved promoting to industry the results of FRDC Project 1998/204, other related information obtained through a literature review and the results of the fish behaviour studies. The project promoted extensive face-to-face meetings with industry members, an industry workshop and presentations to SETFIA, SETMAC, GABMAC as well as port meetings. Various promotional materials were developed including a video, notes on the construction of modified codends for industry members, two posters, and nine published articles in SeaNet News, South East Trawl Fishery News, and Fishing Future promoting gear modifications for bycatch reduction and promoting the research project.

Trials of modified codends by industry were undertaken by encouraging commercial fishers to assess for themselves the benefits of modified codends. Gears promoted for trial included codends with diamond mesh >90 mm, codends with square-mesh panels of 90 mm or greater, single-braid netting and codends with T90 panels or lengtheners. These different materials were sent to fishers on 30 different vessels operating throughout the CTS and GABTS in NSW, Victoria and South Australia.

The effectiveness of T90 panels were investigated by comparing catches of a 90-mm diamond-mesh codend with and without panels (fished together as a trouser trawl). A total of 16 deployments were undertaken, with lower overall catches in the trawl with the T90 panel, especially for small (<30 cm TL) fish. The T90 panel was particularly effective when oriented upwards. Species for which there was clear evidence of increased escape in the codend with the T90 panel included gurnards and leatherjackets. The only species to have greater escape when the T90 codend was orientated downwards was Jack Mackerel and Stinkfish.

Examination of logbook records revealed that by 2005, 7% of otter-trawl effort involved using square mesh. For tows with diamond mesh, 2% were using mesh <90 mm (prawn fishing), 58% with 90–99 mm mesh, 35% with 100–119 mm mesh and 5% ≥ 120-mm mesh. After an October 2005 meeting with SETFIA at which they supported the need for improved legislation regarding codends, legislated minimum gear specifications were changed in December that year. Changes required demersal-trawl codends (excluding Scottish seine) to use 90-mm single twine mesh; or double-twine mesh of at least 102-mm or greater; or 90-mm double twine mesh with a BRD (square-mesh or T90 panel). Fishers were encouraged to use codends with T90 panels or T90 lengtheners/extensions.

NSW DPI project (2004): Improving selection in south eastern Australian whiting (Sillago spp*.) trawls: effects of modifying the body, extension and codend*

Broadhurst *et al.* (2005) undertook this research as a step towards developing a modified trawl within a triple-rig configuration that selectively harvested Eastern School Whiting. The work was done in three experiments off Forster, NSW that aimed to evaluate the effects on the size and species selectivity of trawls due to: (1) a 40% increase in mesh size used in the body, (2) altering the configuration of mesh in the codend; and (3) a separating grid in the extension section (between the body and the codend).

The results showed that increasing mesh size in the trawl body from 45 to 63 mm had no effect on any catches and that, while the grid had the potential to improve species selection by excluding large animals, further refinement and testing were required to minimise the escape of commercial-sized Eastern School Whiting. Changing the orientation of mesh in the codend from diamond (40-mm mesh opening) to square shaped (41-mm mesh, hung on the bar) had a highly significant effect on the size selection of Eastern School Whiting, reducing the catches of individuals <17 cm TL by up to 99%, with minimal impact on the retention of larger, commercial-sized individuals.

Broadhurst *et al*. (2005) concluded that prawn trawlers targeting Eastern School Whiting in NSW waters could be permitted to use a trawl with a larger mesh size in the body (e.g. 63–75 mm), but that this would need to be attached to a square-mesh codend with a bar length approaching 20 mm (i.e. 40-mm mesh hung on the bar). This modified trawl would minimize the fishing mortality of nearly all juvenile and maturing Eastern School Whiting. However, the trawl concept was not mandated, adopted or progressed.

NSW DPI project (2006): Assessing the effects of codend circumference and twine diameter on selection in south-eastern Australian fish trawls

In response to the declining catch rates of many trawl species across outer shelf and upper slope depths (100–500 m) during the late 1990s, central NSW fish trawlers directed more effort onto inshore grounds to target Eastern School Whiting. Because the retention of Eastern School Whiting in conventionally rigged fish trawls with 90-mm mesh codends is very low, local fishers experimented with their trawl designs to increase catches while still complying with the minimum mesh size for the fishery. A common modification was to double the codend circumference to 200 meshes which, when joined to the 100-mesh extension section immediately anterior to the codend, effectively reduced the lateral openings of the codend meshes. In addition, the codends were constructed of 5-mm diameter double twine netting which further reduced the mesh openings.

To provide information on the fishery and gear, Graham *et al.* (2009) assessed the effects of different codend circumferences and twine diameters on the selectivity attributes of ~90-mm diamond-mesh codends when targeting Eastern School Whiting. Specifically, two experiments examined the relative efficiencies and selectivities of five codends made from 90-mm, double-twine mesh but with different circumferences (100 and 200 meshes) and twine diameters (3, 4, and 5 mm). The codends were interchanged with a fine-meshed control in alternate-haul comparisons.

There was a general trend of reduced selection by the 200-mesh circumference and thicker-twined codends, and particularly by the industry-preferred design of 200 meshes circumference constructed from 5-mm diameter twine. Compared with the more-lightly constructed codends, significantly greater numbers of total catch, retained catch, and Eastern School Whiting were caught by the 200-mesh, 4- and 5-mm twined codends, and also significantly more Longspine Flathead in the latter. Across all codends, the smallest lengths at 50% probability of retention were estimated for Eastern School Whiting, Longspine Flathead, Redfish and Longfin Gurnard in the 5-mm 200-mesh codend. Data for Eastern School Whiting showed that an increase of twine diameter from 4 to 5 mm in the 200-mesh codends reduced the average lateral mesh opening from ~24 to ~16% of the stretched mesh length.

The results demonstrated that the codend configuration used by industry was the least selective, but most effective in retaining commercial quantities of Eastern School Whiting. However, in terms of material costs and optimal selectivity of the target species, the industry configuration performed poorly. It was suggested that a more efficient codend, possibly constructed of smaller, square-shaped meshes, should be developed and used in conjunction with temporal, spatial, and catch restrictions. However, to date, such a revised trawl concept has not been promoted or mandated.

AFMA Project 2007/063: Trials of T90 mesh in the Great Australian Bight Trawl Sector

During the mid 2000s, Knuckey *et al*. (2008) trialled the use of T90 mesh (Figure 5) in the GABTS in a project initiated by the Great Australian Bight Fishing Industry Association (GABIA). The trial was undertaken over one week during which 30 deployments were conducted alternating between T90 and control trawls. Overall, the control caught 11. 3 t of retained catch and 13.2 t of discarded catch, whereas the T90 trawl caught 9.4 t of retained catch and 7.7 t of discarded catch. Retained catches were not significantly different between trawls, but the T90 trawl caught significantly fewer discards (Figure 6), particularly of abundant bycatch species such as sponge, Barracouta, Spikey Dogfish, Australian Burrfish, Jack Mackerel, Rusty Carpetshark and Sergeant Baker.

Although not significant, there was some loss of commercial species with the T90 mesh, but this was inconsistent with greater catches of Bight Redfish and Deepwater Flathead in the control trawl at night, and more Deepwater Flathead by the T90 trawl during the day. No notable differences in length frequencies of Bight redfish and Deepwater Flathead were observed between the control and T90 trawls. An important caveat here is that similar to the findings of Broadhurst and Kennelly (1995), no net monitoring equipment was used. Thus, catches could not be standardized to swept area (which may have differed among trawls).

Deepwater Flathead caught by the T90 trawl appeared to be in slightly better condition than those caught by the control net suggesting that, because of greater lateral mesh openings, T90 trawls might have less turbulence in the codend thus reducing scale and mucus loss. Any implied benefits of increased fuel efficiency while towing the T90 trawls (because of reduced twine area) were not realised.

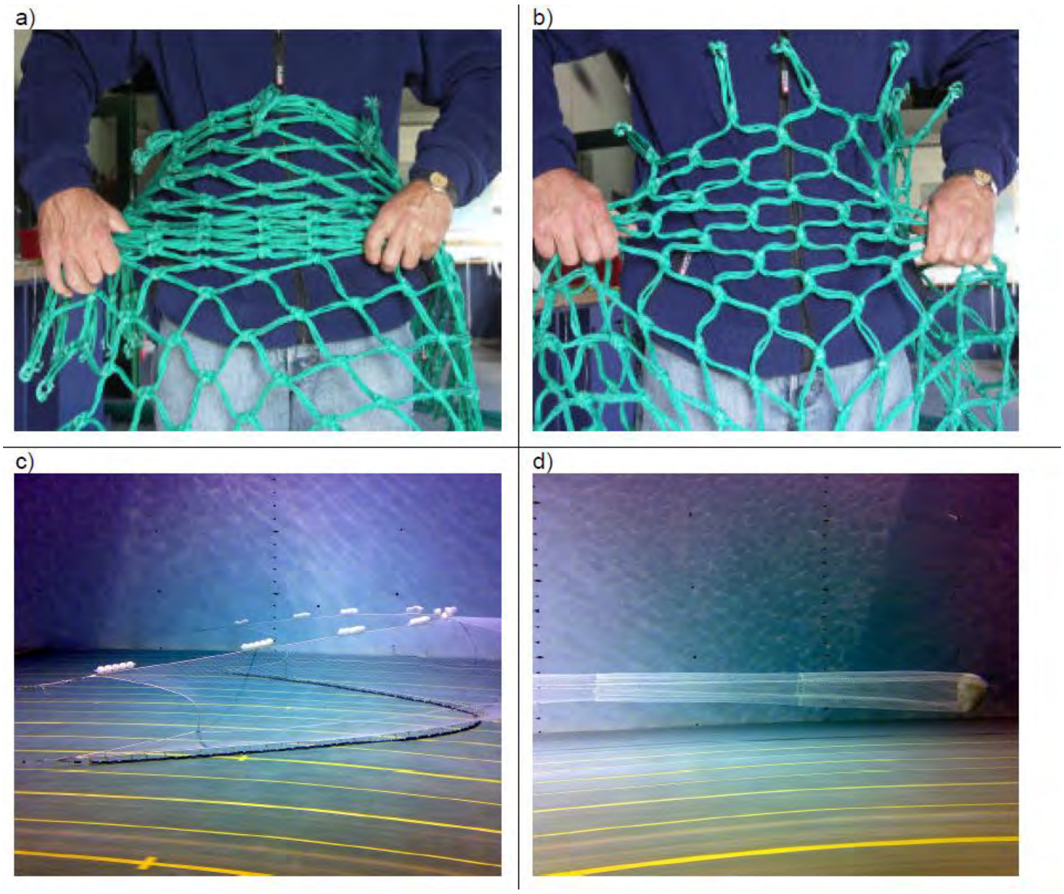


Figure 5. When codends made from conventional diamond-shaped mesh are stretched by the weight of the catch, the meshes close up compared to those that are T90. b) In T90 netting, the meshes are turned 90 degrees and remain more open when the net is stretched. c) The opening of the net during flume tank trials. d) The codend of the T90 net during flume tank trials showing very little turbulence. Photo credits a) and b): SINTEF Fisheries and Aquaculture; c) and d) Hugh McKenna.

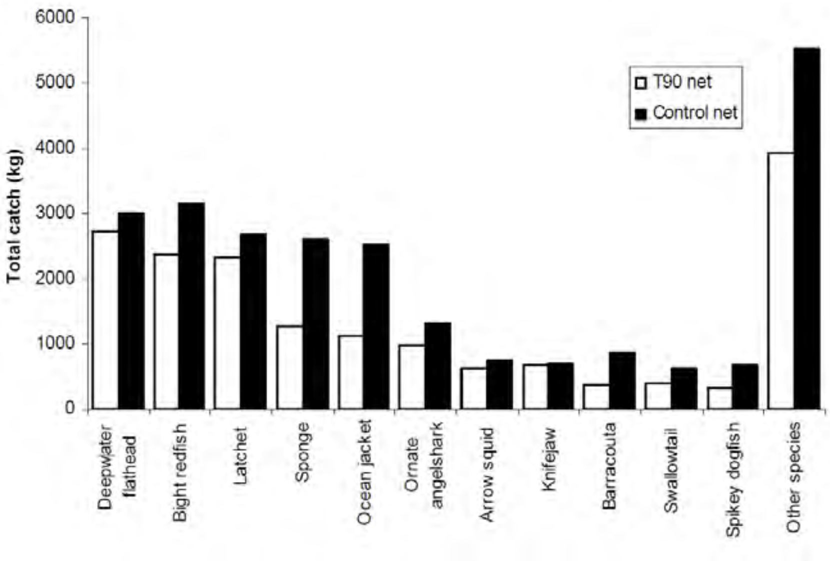


Figure 6. Comparison of catches (kg) of the top ten species caught using the T90 (open bars) and control trawls (dark bars).

AFMA Project 2007/039: Industry Development Subprogram: Field trials of a high-lift trawl net for bycatch reduction

During this work, Koopman *et al*. (2009) trialled the use of a high-lift trawl in the CTS (Figure 7). This high-lift or 'balloon' trawl, was described as having a larger-than-usual top panel to facilitate the escape of small fish, improve the condition of retained fish and was hypothesised to reduce escape mortality because escaping fish should have less contact with netting panels. Control and high-lift trawls were generally alternated over 64 deployments; but data from 22 replicates were omitted because of gear damage and gear-performance issues.

Catches were highly variable (Figure 8). Mean retained catches were nearly identical between trawls and there was no statistically significant reduction in catches of total discards or of high discard species by the high-lift net. However, there were significant reductions in catch rates of Blacktip Cucumberfish (5.26 vs 0.41 kg h^{-1}) and Spikey Dogfish (11.29 vs 2.29 kg h^{-1}). in the high-lift net). Catches of the commercially valuable Deepwater Flathead were significantly less with the high-lift net. There was no difference in the required fuel consumption to tow each trawl; but the quality of retained Blue Grenadier was greater in the high-lift net.

However, as for the earlier project, an important caveat here is that net-monitoring equipment was not used and so catches could not be standardized to swept area (which may have differed between trawls). Also, no trawl plan was provided, precluding future testing in other sectors.

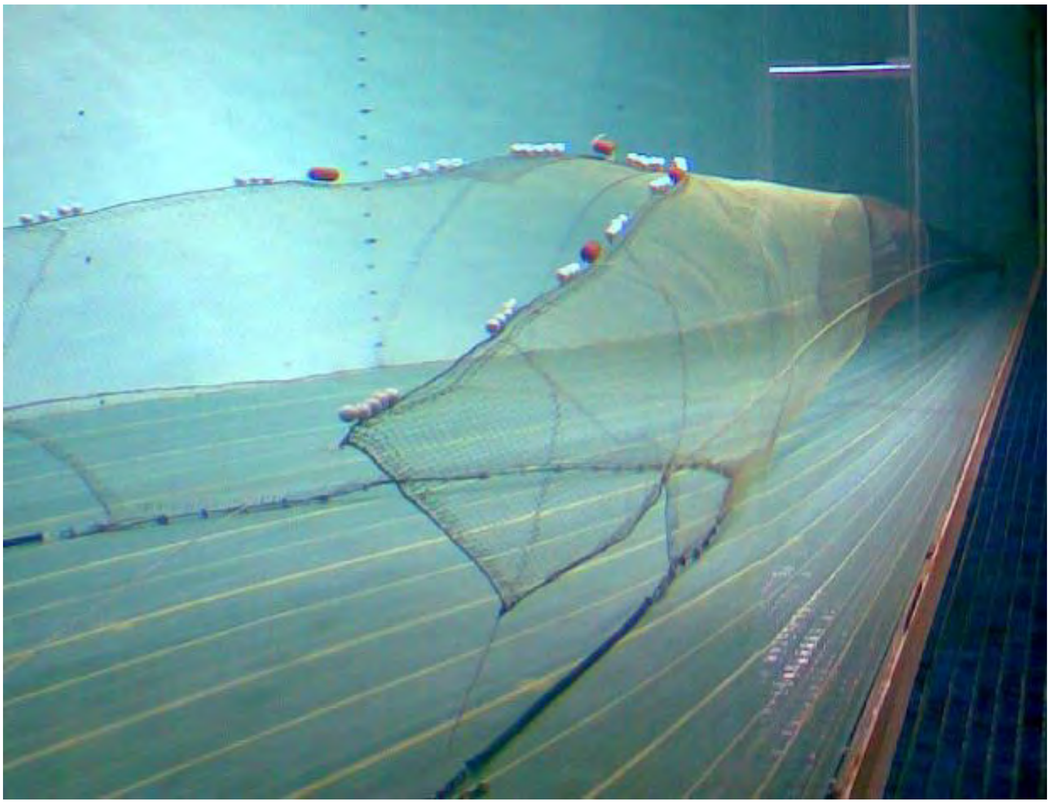


Figure 7. Photograph of a model of the high-lift trawl trialled by Koopman et al. (2009).

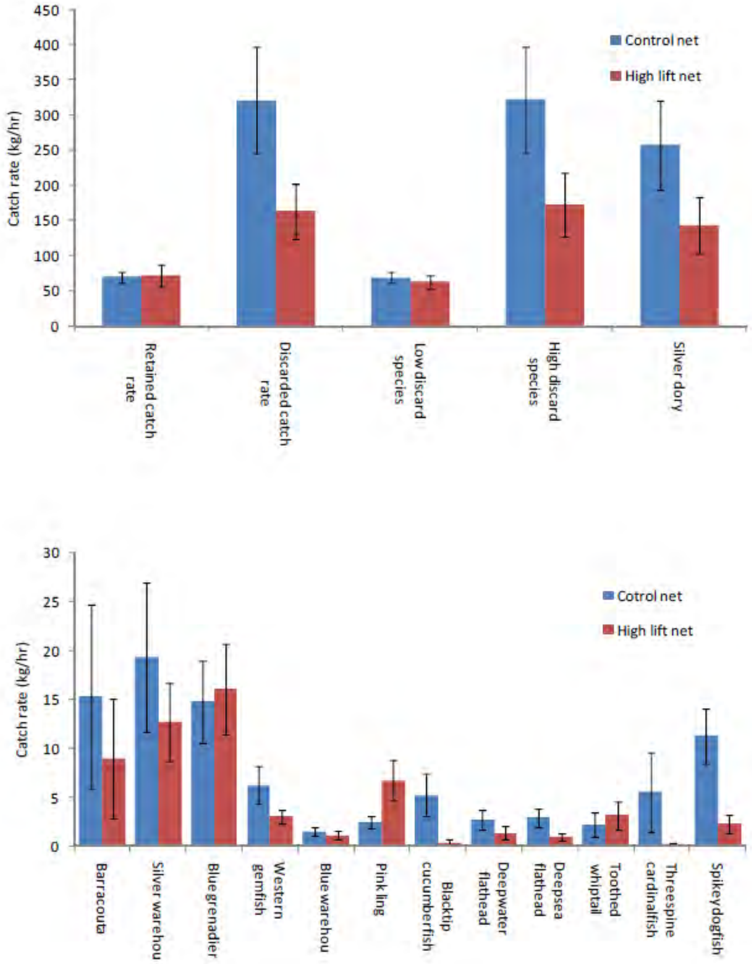


Figure 8. Comparison of mean (±SE) catch rates of retained and discarded species, low and high-discard species and of individual species that were caught in sufficient quantities to enable comparison between the control and high-lift trawls.

FRDC Project No. 2007/040: Selectivity and bycatch reduction of Tiger Flathead and Eastern School Whiting nets in the Danish-seine fishery

Although not entirely relevant to trawlers, selectivity experiments with Danish (Scottish) seines off east Gippsland were undertaken by Koopman *et al.* (2010). This study estimated the selectivity parameters of 65- and 75-mm (SMO) diamond-mesh codends targeting Tiger Flathead using tows with a covered codend, whereas alternate hauls were used to estimate selectivity of 45-mm diamond-mesh codends targeting Eastern School Whiting. The behaviours of fish in the net were quantified from underwater video footage taken during tows targeting Tiger Flathead. Tiger Flathead were observed attempting to escape through the top, side and bottom panels of the codend, suggesting the use of bycatch reduction panels on any side of the codend would result in some loss of that commercially important species.

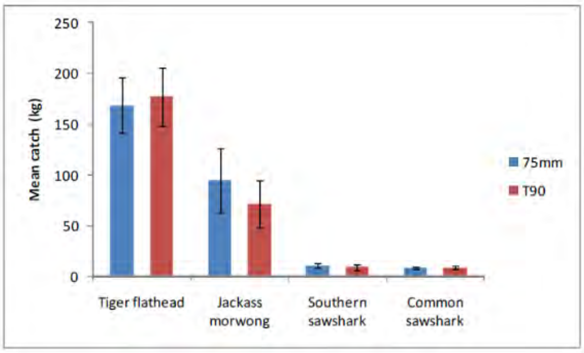
A 75-mm T90 codend was trialled by comparing catches with those from a 75-mm diamond-mesh codend. The results showed that there was no difference in retained catches between codends, but that the T90 codend caught about 27% fewer discarded non-commercial species. The T90 codend caught fewer non-commercial Roundsnout Gurnard and Grooved Gurnard (Figure 9). There were no differences in catches of Tiger Flathead, Southern Sawshark, Ocean Jacket, Latchet, Elephantfish and Red Gurnard. The total length (TL) at 50% selectivity was much larger for the T90 codend (33.5 cm) than for the 75-mm diamond-mesh codend (30 cm). Based on survey catches and the increased market values of large Tiger Flathead, it was estimated that the value of every tonne of Tiger Flathead retained using the 75-mm T90 mesh would be more than $800 greater than those caught using the 75-mm diamond-mesh codend.

The findings suggested that it was unlikely that there would be wholesale uptake of T90 netting by industry because:

- The gear trials did not adequately encompass the full spatio-temporal coverage of the Danish seine fishery, and the size range and availability of Tiger Flathead and other commercial species can vary considerably.
- There was a real and understandable concern amongst commercial fishers that T90 codends may not be suitable at certain times of the year or in certain areas of their fishery.
- The use of T90 netting was a somewhat new and radical change to net making in a fishery that is known for its conservative and traditional approach to fishing techniques across many generations.

Extension of the project results was undertaken by distributing a video describing results to Industry members and with face-to-face meetings with key industry members. Additional extension was facilitated by a Seanet Officer during port visits who would distribute the final report and DVD and discuss results with the fishing industry.

Data from this project were used by SETFIA to demonstrate the benefits of increasing mesh size, which resulted in an industry resolve (with 85% support) to do that. At SETFIA's request, in 2019 AFMA set the minimum Danish seine mesh size when targeting flathead to be no less than 75 mm in any part of the gear.



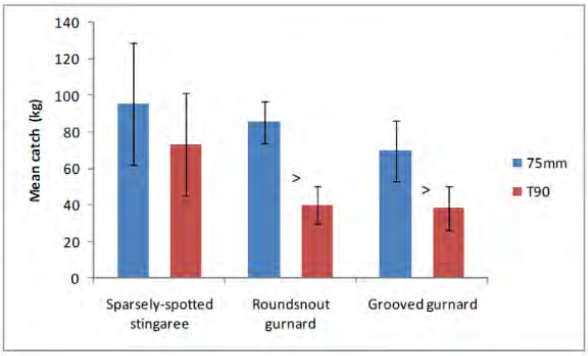


Figure 9. Comparison of mean catch rates for main retained species (left) and main discarded species (right). > indicates significant differences.

AFMA project F2013/3634: Trialling a Gulper Shark excluding device

In this study, Boag and Trappett (2016) tested the efficacy of a Gulper Shark excluder device (GED) while targeting Royal Red Prawns off NSW. The work took place outside of the Gulper Shark closure and, because of the rarity of catches, the project identified Gulper Shark proxies that could be used to evaluate the success of the GED. The GED was an angled aluminium grid stitched into the net to deflect large animals up and out of the net, allowing Royal Red Prawns to pass through to the codend. An underwater video camera was used to record escape. The retained catch was also recorded.

During this project, only four deployments were undertaken, from which 515 minutes of video footage was observed. In total, 78% of sharks escaped through the GED; however 22 sharks were landed on deck. These sharks included the Sawtail Catshark (<60 cm TL), Lanternsharks, Blacksharks, small Prickly Dogfish and Harrisson's Dogfish (~50 cm TL). All skates and rays escaped. Escaped sharks included Piked Spurdogs (~60 to 65 cm TL).

The loss of Royal Red Prawns during the first trip was estimated to be about 26 prawns per minute and was attributed to the steep angle of the GED and a sagging escape flap. The grid angle was reduced for the second trip, and the number of meshes used in the escape cover was reduced to stiffen up the hood. This reduced the loss of prawns.

The authors recommended that AFMA collect data from GED trials undertaken from within gulper shark closures. To date, no further GED trials have been undertaken, although it remains as an action item on the bycatch working plan (AFMA, 2018a).

Surveys to mitigate endangered, threatened and protected (ETP) species

Miscellaneous research on seal excluding devices (SEDs)

Many gear modifications designed to reduce seal interactions will concomitantly reduce catches of large sharks and rays (Kennelly and Broadhurst, 2021; Appendix 4). Knuckey *et al.* (2002) reported on the effectiveness of various fishing practices at reducing incidental seal capture and held an industry meeting to discuss methods of reducing seal bycatch. Potential methods discussed at the meeting included application of an industry code of conduct, deployment of seal excluder devices (SEDs) and the use of seal deterrents.

The evaluation of the effectiveness of fishing practices for reducing incidental seal capture focussed on those included in SETFIA's code of practice, and do not relate to non-ETP bycatch reduction. Of note, SETFIA (2009) trailed the use of SEDs in the CTS. Three SED designs were trialled: the Motnets SED, the Guarnaccia SED and the Bennett SED.

The Motnets SED was constructed of 20-mm stainless steel bar fabricated into three separate grid sections to allow flexibility when being wound around a net drum. The bar was sewn into an extension piece/lengthener at an angle of about 45° from the vertical. On the top panel of the net, a triangular escape hatch, about 1.2 m from the apex to the base was cut along the mesh bars back to the top bar of the SED grid. Over the escape hatch, a hood of 40 mm mesh extended forward (towards the mouth of the net) from the top bar of the SED to a point just forward of the escape hatch apex. A kite was attached to the leading edge of the hood that was made from 300-mm wide conveyor belting designed to provide lift during trawling.

The Guarnaccia SED was made of a polypropylene and metal combination wire and constructed in a way to replicate the Motnets SED. The outside ring was fabricated from 2.5 cm diameter combination wire with the ends swaged together. The vertical bars that were spaced at 23 cm centres were swaged to the outer ring and the spacings maintained with two swaged horizontal bars. The grid was sewn into an extension piece of 90-mm mesh netting at the same 45° angle as the Motnets SED. An escape cover of similar dimensions to the Motnets SED was cut along the mesh bars from the apex back to the top bar of the grid and a hood with kite attached. The entire package could then be inserted into the net joining the codend and extension piece and attached with zipper stitches.

The Bennett SED had seven vertical bars spaced 157 mm apart swaged to each end and to a centre, horizontal cross bar. The vertical bars were 16-mm stainless steel wire covered by polyurethane tube. The outer frame was constructed of stainless-steel tube curved at a small angle giving the Bennett SED a slight overall curve. The flexibility of the SED ensured that it was easily wound around a net drum.

Consistent with trials of the Bennett SED in the Pilbara trawl fishery (Stephenson and Wells, 2006; Stephenson *et al.,* 2006), the escape exit was positioned on the underside of the extension to facilitate removing large rocks and sponge as well as seals from the net. Escape of seals was deemed possible despite the exit being on the bottom of the trawl, because this section was not in constant contact with the sea floor. Stephenson and Wells (2006) and Stephenson *et al.* (2006) showed that this SED configuration significantly reduced unwanted catches of dolphins, large sharks, turtles and large rays. A sock was sewn around the escape hatch to reduce incidental loss of fish. The Bennett SED was trialled on the fishing vessel 'Western Alliance', initially using no flotation.

All of the assessed SED/grids had issues that were not resolved. The Motnet SED did not hold shape transforming into a 'lazy Z' shape during three tows. However, most fish passed the Motnet SED with little escape. Very large skates and rays were impinged against the bars of the SED. No seals were observed entering the net while the Motnet SED was deployed. The Guarnaccia SED was a trial. However, observations of its effect on fish catch were not reported. Nevertheless, one adult Australian Fur Seal entered the net and passed through the SED and into the codend. Soon after, several skates became impinged on the SED, obstructing the seal's escape. During the trial of the Bennett SED, large amounts of commercially important fish were observed to escape, including Blue Grenadier and Blue-eye Trevalla. One seal entered the trawl and was observed to exit through the escape opening during haulingbut the fate of the animal remains unknown. The Bennett SED also suffered from clogging by skates, rays and sponge.

Tilzey *et al.* (2006) trialled the use of SEDs in the winter Blue Grenadier fishery off western Tasmania over four years. The initial SED used in 2000 was similar to TEDs used in prawn fisheries. The SED had a square, backward sloping grid and a backwards facing escape exit on top of the extension. This SED caused significant loss of Blue Grenadier. The SED didn't prevent seal interactions, and the incidence of seal bycatch when the SED was used was about double that of gear with no SED. However, the survival of seals in SED nets was much greater (66%) than those without (22%). The authors suggested that seals were entering the trawls through the escape exit.

In 2001, several different SED designs were assessed, all with forward facing escape exits to reduce fish loss and with larger, square grids. Both top and bottom mounted escape exits were tested. As with the 2000 trial, interaction rates in SED nets were approximately double that of trawls with no SED. These SEDs caused fewer fish to escape than were observed during the 2000 trial, although there were problems with fish accumulating at, and blocking, the SED.

In the following year, both top- and bottom-mounted escape exits were trialled. The SED grid had approximately three times the area of previously trialled grids, and the grids were a near circular shape. The trawl with the escape exit on the bottom of the extension had more seal interactions than a trawl with no SED; but a trawl with the top-opening exit had fewer interactions.

The 2003 trial used the top-opening exit with those SEDs used in the 2002 trial. One vessel used an open exit, whereas another used a closed exit. Overall, seal interaction numbers were low, but the trawl with the open exit had a lower interaction rate compared with that with no SED. Interactions for the trawl with the closed exit were similar to the trawl with no SED.

FRDC Project 2008/048: Dolphin mitigation in Pilbara finfish trawl

This study assessed modified exclusion grids and escape hatches to reduce dolphin bycatch in the Pilbara finfish trawl fishery (PFTF). Bycatch rates varied among vessels and seasons but were lower in the early morning. Dolphin bycatch decreased significantly (by ~50%) when exclusion grids and bottom-opening escape hatches were used in the trawls.

WA Fisheries Research Report No. 244, 2014: Modified trawl nets to mitigate captures of endangered, threatened and protected species

This study assessed traditional modifications (escape exits and grids) in the PFTF (Wakefield *et al.,* 2014). Vessels were fitted with cameras including dual-lens above water and subsurface within-net camera systems to observe interactions. No megafauna exited through a top-opening escape slit. But, an upward excluding grid with a top-opening escape hatch allowed many sharks and rays to escape (except sawfishes). From the findings it was recommended that anterior gear modifications be evaluated to reduce the catches of sawfish and dolphins.

Trawl-gear surveys

Although not assessing bycatch and its reduction, surveys of the gears used have provided important background information and are included here for reference.

FRDC Project 1998/204: SETF trawl-gear survey

This survey was done in what is now the CTS (Graham, 1998). The results comprised survey responses from 55 different vessels from NSW and Victoria. By far the most common otter board type was the steel Vee, ranging in size from 2.1–2.7 m. Other otter boards used included the super-V, curved-V (Thyborum), bison, polyice and flat-wooden designs. The sweeps used in the east of the fishery were mostly 160–275 m and made from 24-mm diameter combination rope, however shorter sweeps of about 90 m were sometimes used on rough seabeds.

Vessels in the west used short sweeps of ~90 m of 24-mm diameter combination rope. East coast vessels used bridles that were mostly 27–37 m of 24-mm diameter combination rope, whereas Portland vessels used 37–46-m bridles with 14–16-mm diameter combination rope. Ground gear mostly comprised rubber tyre discs of 15–25 mm diameter, and chains were only used in NSW. Five basic trawl net designs were described:

- "Spag" (or "Italian"): two-seam trawl with relatively long wings and low headline height (2–4 m). Usually towed around 2.5 knots and often used on the upper slope for Pink Ling, Eastern Gemfish and Redfish.
- "Wing trawl": two-seams, with relatively short wings, moderate headline height (3–5 m). An all-purpose trawl for shelf and slope.
- "Champion": four-seam trawl that is a modified wing trawl with a narrow 5–20 mesh side panel and high headline height (4–6 m). This is an all-purpose trawl towed at 3.0–3.5 knots for Warehou and Trevally.
- "Seastar" or "box trawl": four-seams, with deep, tapered side panels of 35–40 meshes at the bosom, high opening and sometimes rigged with three bridles. Towing speed is 3.0–3.5 knots for Warehou and Trevally.
- Royal Red trawl: Two-seam designs (45–55 m headline length) with very long wings, low headline heights (1.5–3 m), rope ground gear and 40-mm mesh throughout. The trawls are usually towed with 183–275 m sweeps.

Headline lengths on the Spag and wing trawl nets were mostly 40–44 m, whereas 35–39 m was the most common headline length for champion and seastar nets. Mesh sizes in the codend and extensions were all 90 mm SMO. The most common mesh sizes in other parts of the trawls were as follows: 102–127 mm in the lengthener, 152 mm in the back upper belly, lower belly and bunt and 228 mm in the lower and upper wings, front upper belly, and overhang 228 mm. Most trawls comprised 6-mm diameter double braided twine in the codends and 4–6 mm single braided twine in the extensions. In other parts of the trawls, either 60 'ply' or 90 ply twisted twines were most common.

AFMA's 2013 trawl gear survey

Following the predecessor project described above, AFMA (2013) undertook an industry survey of CTS otter trawl gear including questions regarding mesh sizes and orientations. Participation rate was 85% (33 responses from 29 vessels). More than half the respondents reported using a BRD: 13 with T90 mesh panels and four with square-mesh panels. The vessels without a BRD either had diamond-mesh codends made from single twine for 90-mm mesh or double twine in meshes >102 mm.

Most (95%) vessels reported using codend mesh sizes between 90–100 mm, whereas one reported using 105 mm SMO and another 120 mm. Mesh used for the belly of the trawl ranged between 75–300 mm SMO with most vessels using 150 mm. Mesh used in the wings ranged between 100 and 300 mm, with 16 vessels using wing meshes of 230–240 mm and 12 using 150 mm. A total of 30 of the 33 respondents used diamond mesh in their codend, whereas one used square mesh and two used T90 throughout. Most (23 respondents) used single-twine mesh, nine used double-twine mesh and one used both. The length of the trawl from the codend draw strings to the headline ranged between 15 and 50 m, with a mode of 35 m. Ground gear included bobbins, rubbers, rubber discs, rock hoppers and chains, and these were sometimes used in combinations. Most common configurations were bobbins, rubbers and rock hoppers, whereas chain was only used by one operator when fishing for prawns.

Changes to SESSF management arrangements

The various projects and independent work described in the preceding section have facilitated several management changes to technical aspects of trawls throughout the fisheries (

Table 1). These changes have mostly affected the CTS. Nevertheless, there is also clear temporal extension of ideas and concepts to the GABTS, albeit with fishery-specific application. It is also clear that the technical specifications have extended to other Australian fish-trawl fisheries as starting points for permits.

Table 1. Management arrangements that affected fishing gear requirements to the CTS and GABTS (adapted from information provided by provided by Dan Corrie, AFMA).

Date	Sector	Management change	Reference
1965	CTS	minimum codend mesh size of 90 mm applied to single braid mesh	Knuckey *et al*. (2018)
30/06/1998		In the area of the SET, using demersal otter trawl, • if the person fishes for prawn, the mesh size of the net must be o At the codend of the net – at least 40 mm and not more than 45 mm o At any other part of the net – at least 40 mm and not more than 60 mm. • if the person is fishing for any other species, the mesh size of the net must be at least 90 mm at every part of the net. In the sub-area described in Part 1 of Schedule 3 (eastern sector- east of 149˚ 30') using Danish seine gear: • if the person uses a net for fishing, the mesh size of the net must be at least 83 mm at every part of the net. In the sub-area described in Part 2 of Schedule 3 (western sector- west of 149˚ 30') using Danish seine gear: • if the person uses a net for fishing for a quota species (except school whiting or flathead), the mesh size of the net must be at least 83 mm at every part of the net; • if the person uses a net for fishing for school whiting or flathead or a non-quota species (except school shark or gummy shark), the mesh size of the net must be at least 38 mm at every part of the net.	https://www.legislation.gov.au/Details/F2005L04191
8/01/2003	CTS	Any net used to fish for fish, other than prawns the mesh size of the net must be, when measured in accordance with the manner specified in Schedule 1, not less than 90 mm (3.5 inches) at any part of the net.	Southern and Eastern Scalefish and Shark Fishery Management Plan 2003 Direction No. SESSD 02 Gear Requirements 5.1
9/01/2003	CTS	Any net that is used to fish for prawns then the mesh size of the net must be, when measured in accordance with the manner specified in Schedule 1 or Schedule 2, not less than 40 mm (1.5 inches) and no greater than 60 mm (2.4 inches) at the codend of the net, and not less than 40 mm (1.5 inches) and no greater than 60 mm (2.4 inches) at any other part of the net.	Southern and Eastern Scalefish and Shark Fishery Management Plan 2003 Direction No. SESSD 02 Gear Requirements 5.2
10/01/2003	CTS	Any net is used to fish for fish by Danish seining in the eastern sector of the Danish seine area then the mesh size of the net must be, when measured in accordance with the manner specified in Schedule 1 or Schedule 2, not less than 38 mm (1.5 inches) at any part of the net.	Southern and Eastern Scalefish and Shark Fishery Management Plan 2003 Direction No. SESSD 02 Gear Requirements 5.3
11/01/2003	CTS	Any net is used to fish for fish by Danish seining in the western sector of the Danish seine area then the mesh size of the net must be, when measured in accordance with the manner specified in Schedule 1 or Schedule 2, not less than 83 mm (1.5 inches) at any part of the net.	Southern and Eastern Scalefish and Shark Fishery Management Plan 2003 Direction No. SESSD 02 Gear Requirements 5.4
12/01/2003	GABTS	Any net used to fish for fish the mesh size of the net must be, when measured in accordance with the manner specified in Schedule 3, not less than 90 mm (3.5 inches) at the cod-end of the net.	Southern and Eastern Scalefish and Shark Fishery Management Plan 2003 Direction No. SESSD 02 Gear Requirements 5.5
17/12/2005	CTS	Demersal trawl cod end to reduce bycatch (excluding Danish seine): 90 mm single twine mesh; or double twine mesh of at least 102 mm (4 inch) or greater; or 90 mm double twine mesh with a bycatch reduction device (square mesh panel or T-90).	Knuckey *et al*. (2018) https://www.legislation.gov.au/Details/F2005L04191
20/08/2007	CTS	Continuation of codend, and wing mesh net requirements	SESSF Direction (Minimum Gear Requirements) 2007

20/08/2007	GABTS	Moved minimum mesh net requirements from permit conditions	SESSF Direction (Minimum Gear Requirements) 2007
22 December 2010	CTS	During the period 1 June to 30 September each year, fishing using a factory vessel is prohibited in the area South of 40 degrees S and West of 147 degrees E of the Commonwealth South East Trawl Sector unless a SED is used in every trawl shot and immediately at the conclusion of a shot in which seals are captured, an email is sent to monitoring@afma.gov.au, detailing the number of "alive" and/or "dead" seals.	https://www.legislation.gov.au/Details/F2010L03313
9/07/2012	CTS	For the Commonwealth South East Trawl Sector and East Coast Deepwater Trawl Sector, the following minimum nets requirements apply to otter trawl gear: • Wing and net mouth - The minimum mesh size in the wings and the net mouth (shoulders, belly and veranda) is 115 mm mesh (4 ½ inch). • Codend - The codend must be: o at least 90 mm single twine mesh; or o double twine mesh of at least 102 mm (4 inch) or greater; or o at least 90 mm double twine mesh, with one or more bycatch reduction devices.	Southern and Eastern Scalefish and Shark Fishery (Minimum Gear Requirements) Direction No. 1 2012
9/07/2012	GABTS	For the Great Australian Bight Trawl Sector, the following minimum nets requirements apply: • Mesh size - A net must have a mesh size that is not less than 90 mm (3.5 inches) at the codend of the net.	Southern and Eastern Scalefish and Shark Fishery (Minimum Gear Requirements) Direction No. 1 2012
1/05/2019	CTS	Danish seine mesh size needs to be no less than 75 mm at any part of the net when targeting flathead.	https://www.setfia.org.au/danish-seine-fishermen-act-to-protect-juvenile-flathead-stocks/ https://www.afma.gov.au/sites/default/files/sessf_management_arrangements_booklet_2019_final_updated_july_2019.pdf

Preliminary analyses of observer and logbook data

Logbook data

Analyses of the time series of codend mesh sizes indicated considerable variation (Figure 10); with zones separated into NSW, east and west CTS and GABTS). Specifically, maximum mesh sizes appeared unrealistically large in some years. Nevertheless, these large values for mesh sizes occurred across all regions. Some minimum mesh sizes also appear to be unrealistically small, contravening the regulations, although it is possible that some of these were a part of research projects fished under scientific permits. Future analyses should filter the data for unrealistic values of mesh size, but without greater context any attempt here would be potentially spurious. Records of Royal Red Prawn nets in the east, west and GABTS are almost certainly errors. Accordingly, for the purposes of this review, no overall trends could be determined with any certainty.

Irrespective of sizes, diamond mesh was by far the dominant orientation throughout the time series for the east, west and NSW, and also in the GABTS from 2002–12, after which T90 and square mesh were used for most deployments (Figure 11). It is also clear that the use of T90 mesh has exceeded the use of square mesh in the past two years. The use of square mesh has decreased since 2011 in the CTS and since 2007 off NSW (fish-trawl fishery). By comparison, square mesh has been used in the west since 2003, whereas T90 mesh has been used since 2016.

The use of BRDs has increased in all regions since 2013 (Figure 12). However, in most regions the application of BRDs remained largely unreported until recent years. Square mesh was the main BRD reported in the east, whereas single-strand codend twine was used in lieu of BRDs off NSW. Fishers working in the GABTS reported using T90 extensions and T90 codends, with the latter most common in recent years. Indeed, T90 codends and “T90 unknown” were the most commonly reported BRDs in the west.

Figure 10. Maximum (blue), mean (green) and minimum (red) codend mesh sizes of fish and Royal Red Prawn trawls by zones recorded in logbooks. Data were first filtered to get unique combinations of vessel name, net type, zone, year and codend mesh size.

Figure 11. Number of deployments (shots) undertaken by fish trawls using different mesh types by zones recorded in logbooks. D= diamond; S = square; T = T90; and O = Other.

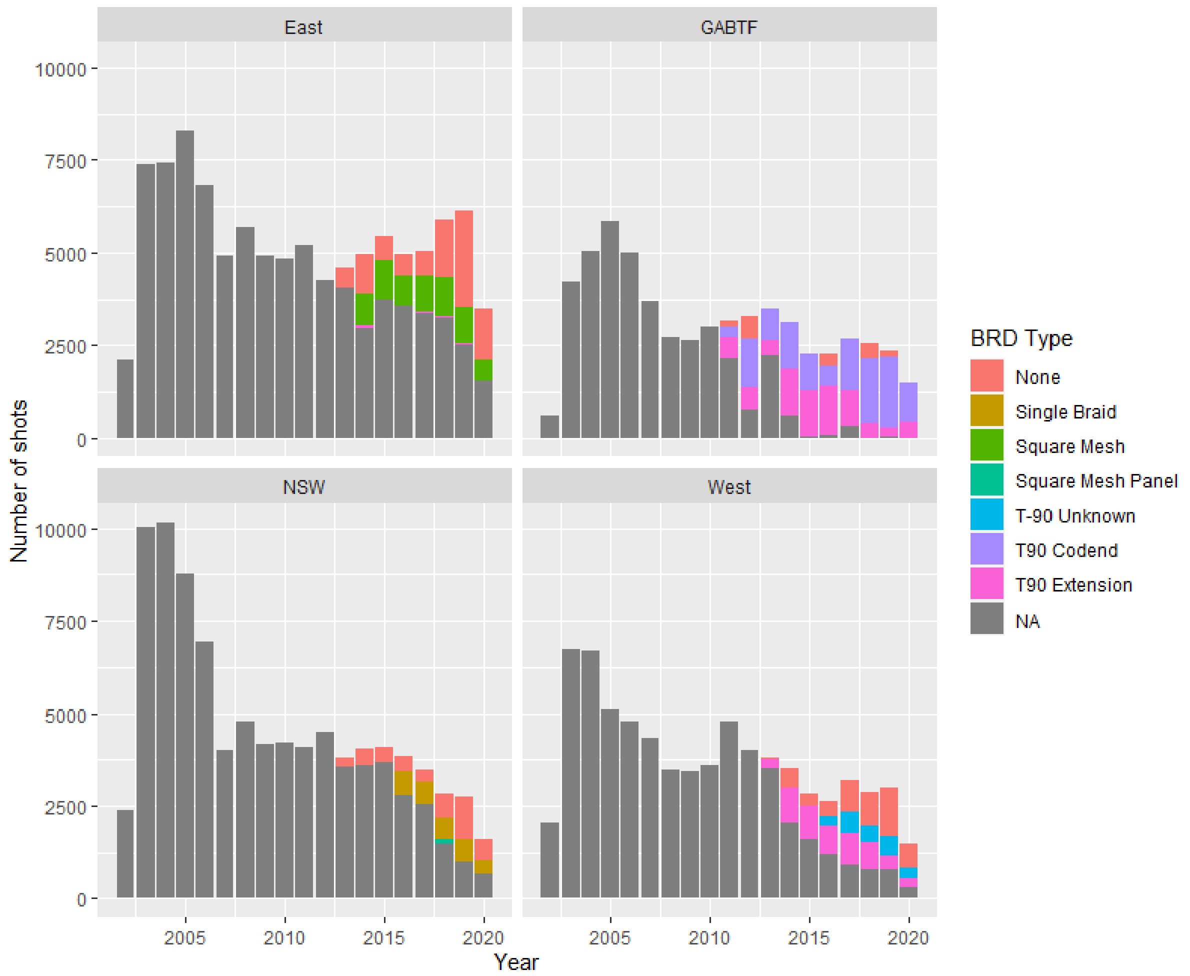


Figure 12. Number of deployments (shots) undertaken by fish trawls using different specific bycatch reduction (BRD) types by zones recorded in logbooks

Observer data

Other than targeted fishing of Orange Roughy and Blue Grenadier, observer coverage of market fishing trips by SESSF trawl vessels is relatively low (2–5%). Again, we remain uncertain how robust the observer recordings of codend mesh size are. Mean mesh sizes recorded from observer data have been relatively steady in the east and off NSW since 2004 (Figure 13). Mesh sizes on vessels observed in the west appeared to decrease after 2005, and then increase again after 2017. Not surprisingly, given the small number of vessels and low sampling effort, mean mesh sizes in the GABTS vary substantially among years. The very large mesh sizes observed in the logbook data are also present in the observer data; but this does not preclude them being errors.

"None recorded" is the most common category of BRD in observer data (Figure 14). Turned 90 and square-mesh codends and square-mesh panels were all recorded in the GABTS. It is uncertain if the observers from 2018 and 2020 recorded whether a BRD was used or not. Relatively low numbers of deployments off NSW and the east were recorded as having BRDs, together with small numbers of T90 sections, square-mesh codends, square-mesh panels and codends comprising single-strand twine. When recorded, the mesh orientation of codends has been mostly diamond, with small numbers of square-mesh codend deployments in each region (Figure 15).

The length-frequency distribution of retained catches associated with each mesh size and orientation was also examined. However, the numbers of samples for each length frequency distribution was considerably reduced from the original dataset because of a lack of reported mesh size by observers. Thus, sample sizes in the CTS were generally too low to produce consistent length-frequency distributions. Insufficient records of mesh orientations other than diamond were recorded, precluding meaningful comparisons in the east, NSW and the west. Further, no consistent patterns in length-frequency with codend mesh size is evident in the GABTS data. Further work will be required before the observer data can be analysed in this manner.

We also used the observer data to examine the overall discard rate associated with each mesh size. However, this did not reveal any clear patterns (Figure 16). Nevertheless, until filtering and further analyses are conducted, these results should be treated with caution, particularly where mesh size is recorded as being <90 mm.

It should be noted that, together with other priorities for research, some of the deficiencies associated with the current observer work are encapsulated within the most recent CTS and GABTS work plans (Table 2). It is imperative that accurate observer data are collected to support any priority actions undertaken by willing fishers. Even subtle variations in gear specifications could greatly affect the conclusions of trials (formal or otherwise) in assessing technical modifications of fishing gear to improve selectivity.

Table 2. Action items relating to bycatch reduction in the most recent (2018–19) CTS and GABTS work plans (AFMA, 2018).

Sector	Action item	Description
CTS	1. Continue the online learning module for bycatch issues in the SESSF.	Improving skipper/crew education on bycatch issues in the SESSF.
	3. Further develop the SESSF Trawl Discard Strategy.	Improve reporting of discards.
	4. Investigate work on seal mitigation in trawl fisheries.	Improve understanding of seal interactions and available mitigation options (desktop study).
	6. Trial the Gulper Shark Exclusion Device (GED).	Proof of concept trials are complete. Allow for prawn trawling in gulper shark closures.
	9. Investigate hinged Seal Excluder Devices for otter board trawl vessels.	Reduce interactions with seals.
GABTS	1. Further develop the SESSF Trawl Discard Reporting Strategy.	Improve the reporting of discards.

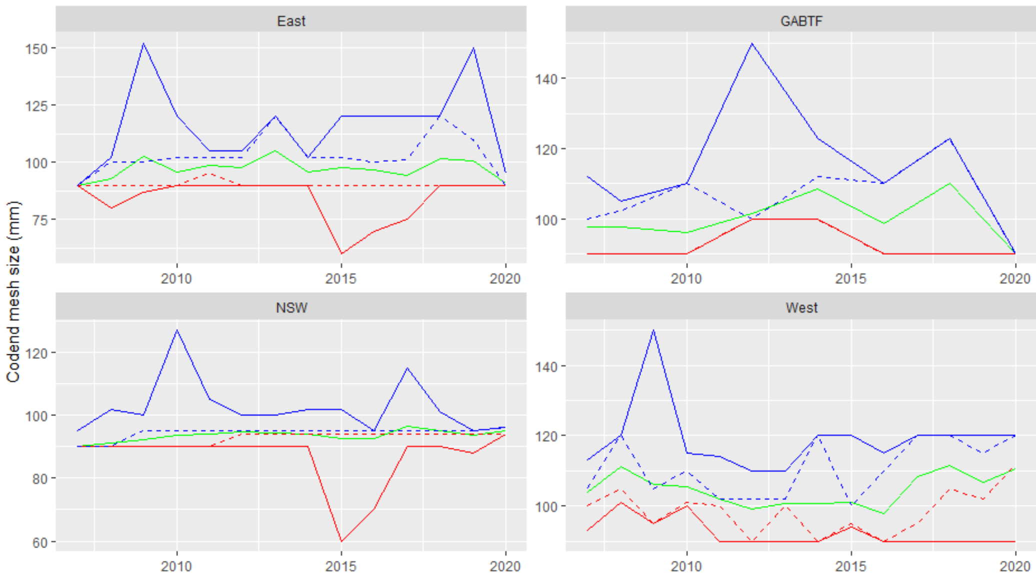


Figure 13. Maximum (blue), mean (green), minimum (red), 25th quantile (red dotted) and 75th quantile (blue dotted) codend mesh sizes of fish observed for otter trawls by zones. Raw data were used, so there were data points for each deployment.

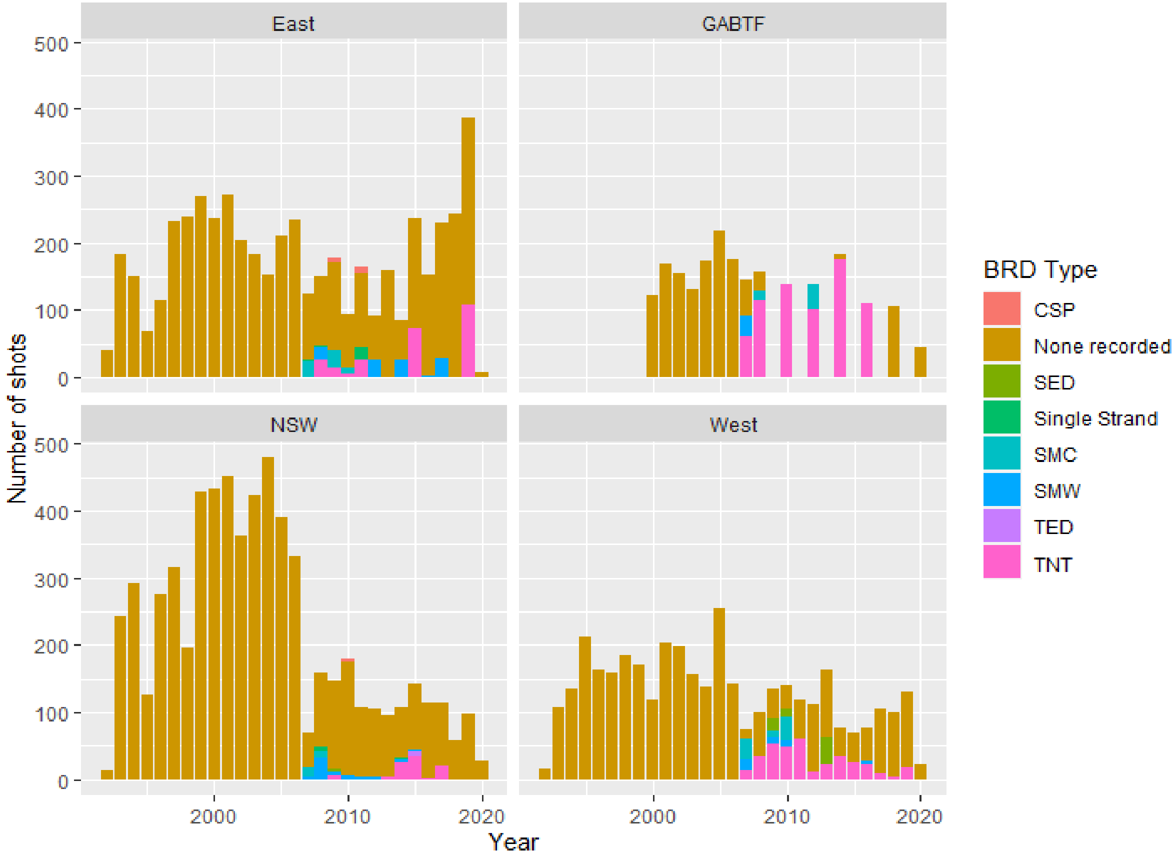


Figure 14. Number of observed deployments (shots) undertaken by fish trawls using various bycatch reduction devices (BRDs) by zones. CSP= Composite square mesh panel; SED = Seal excluder device; SMC = square mesh codend; SMW = square mesh window; TED = turtle excluder device; TNT = T90; and OTH = other BRDs.

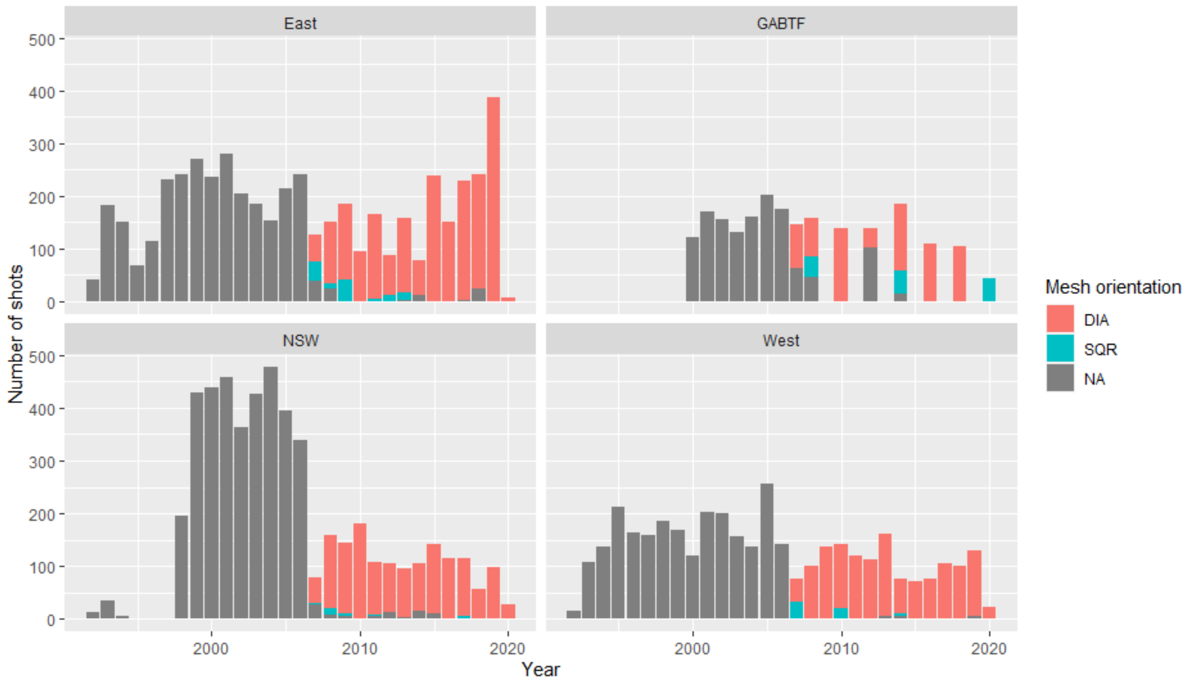


Figure 15. Number of observed deployments undertaken by fish trawls using diamond (DIA) or square-shaped (SQR) meshes in codends by zones. NA = not available.

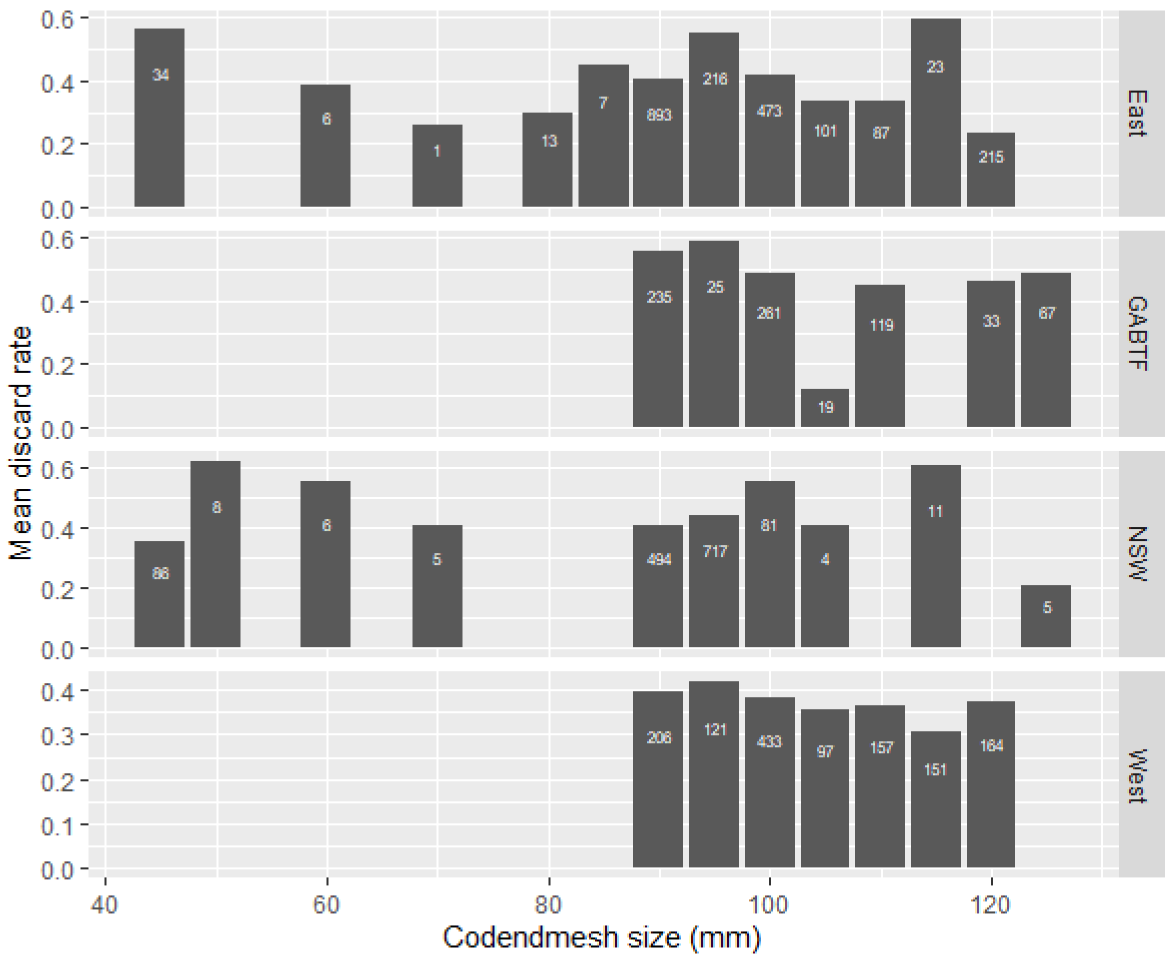


Figure 16. Mean observed discarded rate (D/(R+D)) by codend mesh size (mm), with the numbers of deployments written in each histogram.

Discussion

Bycatch in demersal otter-trawl fisheries has long been recognised as an issue in Australia (Kennelly, 1995) and internationally (Morizura *et al.,* 2004). Otter trawls often are poorly selective fishing gears which nearly always catch species too small for market, or those considered unmarketable or listed as ETP. In Australia, there have been numerous efforts aimed at reducing bycatch in fish trawls focussed mainly on two areas: (1) avoiding small unmarketable fish; and (2) minimising interactions and/or catches of ETP species, most notably seals and dolphins in the southern regions and dolphins, turtles and large sharks in northern regions. Minimum mesh sizes are implemented throughout all Australian fish trawl fisheries to help address the former. The utility of various BRDs (TEDs, SEDs, and GEDs) to mitigate the latter ETP interactions have been trialled in the different fisheries with differing levels of success.

In line with the objective of the Commonwealth Fisheries Bycatch Policy, the Australian Fisheries Management Authority is "*committed to bycatch reduction, improved protection for vulnerable and threatened species and minimising any adverse impacts of fishing on the marine environment*". Specifically, bycatch and discarding workplans aim to reduce the number of high-risk species interactions through ecological risk assessments (ERAs), reducing discarding of target and non-target species to as close to zero as possible, and minimising overall bycatch in fisheries over the long term. Achieving these outcomes requires collaboration between fisheries managers, scientists and industries, and close assessment of the available options with regards to successful cases both nationally and internationally.

Generally, it is accepted there are two broad methods for reducing bycatch via technical modifications in trawls. The first involves 'mechanical separation', whereby either the passage of bycatch species into the codend is blocked by BRDs guiding them to openings in the net or where mesh size or orientation mechanically filter individuals based on sizes. The second method is termed 'behavioural separation', with species-specific differences in behaviour used to either direct an unwanted species away from the trawl (i.e. before entry), or if they enter the trawl, then to a strategic escape opening. Often BRDs in trawls operate on both principles. Most BRDs tested in Australian fisheries, including the CTS and GABTS are based on the former as starting points. But the review by Kennelly and Broadhurst (2021; Appendix 4) demonstrates comparable results have been achieved in overseas fisheries by concentrating on the second category and especially in the anterior trawl. Doing so has, in many cases, also realised benefits in terms of reduced drag and therefore improve fuel efficiencies which can promote industry uptake.

Nevertheless, the available literature suggests the starting point for any attempt at improving selection in fish trawls is mechanical separation by controlling the correct mesh size and shape. Covered codend work by Knuckey and Ashby (2010) in the SESSF revealed how effective this approach can be, with the standard 90-mm diamond-mesh codend enabling >30% by weight (>80% by number) of all small fish that entered the trawls to escape through the codend (and into a cover). They also showed that bycatch reduction could be simply achieved with larger codend mesh sizes, but there was usually some loss of commercial catch. This work, and a subsequent project to promote industry uptake of gear modifications (Walker *et al*., 2010), resulted in an industry supported change to the legislation specifying that any otter trawl used in the CTS to target fish must have either 90-mm single twine mesh; double twine mesh of at least 102 mm or greater or 90-mm double twine mesh with a BRD (square mesh panel or T90).

Despite the above and other bycatch reduction work in the SESSF, the effectiveness of these gear restrictions are not immediately evident from initial analysis of the logbook or observer data. This is likely due to various factors including historically zero or poor recording of discards in commercial logbooks and lack of consistency and rigour in the recording of codend mesh sizes in commercial logbooks and observer data. Although there has been marked improvements in data quality in recent years, specifically due to the mandatory requirement for electronic logbooks, the changes are too recent to capture the results of the gear changes that occurred around 2010. It is hoped that a future, more forensic filtering and analyses of ongoing commercial logbook and observer data may overcome some of these issues.

Another reason for the lack of a clear signal between bycatch reduction and the implementation of larger mesh size and/or escape panel is that fishers can modify the construction and use of their gear to minimise fish loss despite simple gear restrictions. Graham *et al.* (2009) demonstrated that the effectiveness of mesh size restrictions can be easily undermined by fishers through other gear modifications such as increasing twine diameter and codend circumference. These outcomes support modifications that not only improve selectivity, but also efficiencies. Fishers are less likely to handicap intended selective gears if they concomitantly reduce drag and fuel.

Notwithstanding the above, it should be reinforced that some changes without ancillary benefits are voluntary adopted in the spirit of regulation. For example, notwithstanding experimental design limitations associated with no trawl-monitoring equipment, a trial of T90 mesh in the GABTS (Knuckey *et al*., 2008) demonstrated its effectiveness in reducing some bycatch. More importantly, there was an improved condition of retained Deepwater Flathead. Rather than being mandated, the uptake of T90 mesh in the GABTS was voluntary, assisted by the small number of vessels in the fleet, an active representative association, and also the more recent evidence of no effects on catches (Appendix 7).

While several changes in the CTS and GABTS have been positive, because the fisheries are dynamic with variable target and quota species, at some times and locations, large numbers of unwanted species are still caught and discarded. With regard to general bycatch reduction, Kennelly and Broadhurst (2021) demonstrated that 70% of the gear modifications around the globe have occurred at the codend, but significant improvements in bycatch reduction can also be achieved through modifications before the trawl (doors, sweeps, and bridles) at the front of the trawl (footrope, headline and lead-a-head) and at middle of the trawl in the extension. We propose similar ways forward for the CTS and GABTS. More specifically, concerns that the mandatory requirement for maximum rubber and disc diameter on the footropes of NSW fish trawls results in higher level of bycatch, were brought to our attention during the current study. Excluding the trials of a high-lift balloon trawl, all of the formal research in both the CTS and GABTS to date has focussed on codend modifications to reduce general bycatch. However, as part of daily fishing activities, industries have trialled a far broader range of modifications including changes to the extension, headlines and footropes. Formal testing of some of the more promising of these modifications supported the objectives of the current project.

While we propose that anterior modifications should receive a high priority in future work, it is also clear that for problematic ETP species, mechanical-type BRDs in the codends are likely to remain a feature. Specifically, work on the design, implementation and effectiveness of grids and other exclusion devices to mitigate capture of large ETP in fish trawls has attracted more research focus than general bycatch issues, largely due to public concern and pressure to quickly address trawl captures of "charismatic megafauna" such as seals, dolphins, turtles and large sharks. Such excluder devices have been extremely effective when implemented in prawn trawl fisheries (e.g. NPF and NSW estuarine prawn fisheries) because of the differences in sizes between the target species and by unwanted bycatch. The difficulty in implementing excluder devices in fish trawls is that many of the target species can be quite large and the modifications can easily evoke significant losses of the valuable target species.

In addition to the well-documented capture of seals in the CTS (midwater and demersal) trawls, catches of other megafauna such as large elasmobranchs (sharks and rays) in both the CTS and GABTS are of increasing concern and they have been highlighted as a high risk in the revised ecological risk assessments (Sporcic *et al*. 2019, 2020). Apart from the mandatory implementation in the Blue Grenadier spawning fishery to reduce the capture of seals, use of excluder devices in the SESSF, although trialled in small and ad hoc projects, has been largely unsuccessful. This represents an area of potential value for exploration in the current project.

A recent ERA identified several high-risk species for SESSF trawl fisheries (Sporcic, 2019). For the CTS, final risk scores were assessed as high for Bight Skate, Longsnout dogfish, and as extreme for Leafscale Gulper Shark, Southern Dogfish, Gulper Shark and Endeavour Dogfish. There were no high risk or extreme risk species for the GABTS; but large catches of Wide Stingaree and Ornate Angel Shark have been highlighted as issues that may warrant resolution. The main protected species caught in trawl nets in the SESSF are Australian Fur Seal New Zealand Fur Seal and Common Dolphins, while the fishery also catches the IUCN listed Porbeagle and Shortfin Mako.

In terms of possible options for mitigating catches of large unwanted species, two BRDs (for Gulper Sharks and seals) have been trialled in the CTS but not adopted: the GED (Boag and Trappett, 2016) and SEDs (Knuckey *et al.,* 2002; SETFIA, 2009). The GED showed promise in allowing small sharks and rays to escape, while minimising the escape of Royal Red Prawns, however only a small number of deployments were undertaken. The authors recommended additional fieldwork, particularly in areas closed to fishing to protect Gulper Sharks, however this has not been done. Seal exclusion device trials revealed several issues including grids folding over, blockage from skates, rays and sponge, and excessive loss of targeted fish. These issues have never been resolved, but Kennelly and Broadhurst (2021; Appendix 4) provide examples of other devices used overseas that might be applicable.

Interactions with listed seabirds have been significantly reduced via the vessel specific seabird management plans that include the use of one of three specified seabird mitigation devices. One of the first of these devices to be implemented—a warp deflector called a 'pinkie'—was shown to reduce warp strike by 75% (Pierre *et al.*, 2014). Rather than relying on voluntary uptake, use of the pinkies was mandated. Subsequently, an industry-led project demonstrated the efficacy of two other seabird mitigation devices in the CTS—a baffler and a water sprayer (Koopman *et al.,* 2018). Importantly, industry members were principal investigators of the project and designed and built these devices while fisheries managers were involved in overseeing the project, but data collection describing minimum standards and the field trials were undertaken by independent scientists on commercial vessels. This collaboration resulted in industry buy-in, and a quick inclusion of these mitigation devices for use in seabird management plans. Although further work on this area for the current project is not a priority, the framework followed should form the basis of any work plans moving forwards.

Moving forwards, there are a plethora of options for gear modifications, including some already used by local industries (e.g. T90 extensions in the GABTS) and overseas, that could address the issues currently facing the SESSF. Priority should be given to mitigating catches of species identified as high risk by ERAs and those that are protected or managed under stock rebuilding strategies and threatened habitats. We recommend following a protocol of close stakeholder consultation in confirming the utility of variations to mesh sizes and BRD configurations in codends (including devices to reduce megafauna) where relevant, and also focus on new modifications to the anterior trawl. The advantages of the latter type of changes are that they might concomitantly improve efficiencies (by reducing drag) and perhaps equally important, increase the probability of organisms surviving after escape (because they avoid interactions inside codends). We are confident that through adaptive technological options identified in our reviews of the national and international literature, unwanted bycatches can be considerably reduced in the CTS and GABTS to satisfy the requirements of the Commonwealth Fisheries Bycatch Policy (DAWR 2018b), while increasing efficiencies.

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REVIEWS

A review of bycatch reduction in demersal fish trawls

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Abstract Otter trawling for fish is one of the world's most productive yet problematic fishing methods due to its bycatch and discards; issues that have been mitigated in some fisheries by developing more selective trawls. This paper systematically reviews efforts published in international peer-reviewed papers over the past 30 years to identify beneficial (and limiting) factors and propose a way forward in this field. In total, 203 papers were assessed, encompassing many of the world's fishing regions, and involving > 147 species, although 74% of efforts occurred in Europe mainly focussing on haddock (*Melanogrammus aeglefinus*) (64 papers) and cod (*Gadus morhua*) (59 papers). Common, simple modifications have involved increasing lateral-mesh openings to match the morphology of unwanted catches via larger diamond-shaped mesh, or simply turning meshes 45° or 90°, either throughout codends or as strategic windows in the posterior trawl. In some fisheries, more complex grids have improved size or species selection. Fewer attempts have been made to modify the anterior trawl, but varying sweep/bridle lengths, horizontal separator panels and longer headropes have realized benefits depending on species-specific behavioural responses. While the utility of many modifications is indisputable, experimental designs (mostly involving covers, but also alternate hauls and paired comparisons) have, in many cases, suffered low replication and/or confounding variables. These deficits may have compromised some results and contributed to repeated efforts in particular fisheries. We conclude that rigorous empirical assessments, initially focusing on the posterior trawl, but eventually encompassing anterior changes, combined with straightforward interpretation of results for stakeholders, are as important as the simplicity and reliability of modifications. Finally, by assessing the utility, applicability, advantages and disadvantages of the modifications developed, we provide a framework which could be followed in future work to reduce bycatch in these fisheries.

Keywords Bycatch · Discard · Demersal fish trawl · Multi-species · Selectivity

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Introduction

The problem

Despite many years developing more selective fishing methods, bycatch (i.e. organisms that are unintentionally caught) remains a key issue for fisheries management, policy and science (FAO 2011; Gilman et al. 2020). Demersal otter trawling for fish (hereafter referred to as 'fish trawling' and the gear as 'fish trawls') is a major contributor to global seafood production; but is also responsible for 25% of the world's discarded bycatch (estimated at 9.1 million t in total; Pérez Roda et al. 2019). Concerns from the public and interacting fisheries regarding impacts associated with large collateral mortalities of discards, eco-labelling certification initiatives like the Marine Stewardship Council, and the recent implementation of the European Union's Landing Obligation (or 'discard ban'), have placed fish trawling at the forefront of mitigation efforts, with hundreds of studies being done—especially in the past few decades (Broadhurst et al. 2006; Uhlmann et al. 2019).

Many of the world's fisheries jurisdictions seek to reduce bycatch from fish trawls, but most research has occurred at relatively few locations, and in many cases concentrated on technological modifications to conventional trawls designed to improve either size or species selectivity. While there exist several regional reviews (e.g. Kennelly 1995; Pol and Carr 2000; Valdemarsen and Suuronen 2003; Graham et al. 2004a, b; Graham 2006; Madsen 2007; Suuronen and Sarda 2007; Madhu 2010; Feekings et al. 2013), there has been no systematic, global synthesis of the many fish-trawl studies that have been done. Such a review should prove useful to those jurisdictions/fisheries beginning work in this area and/or that fall outside the regions where research has concentrated, and complement broader efforts to reduce the wastage and environmental impacts of fishing gears in general (e.g. Broadhurst 2000; Wenger et al. 2017; McHugh et al. 2017; Pérez Roda et al. 2019).

Our objective in this review was to address the above shortfall by detailing and critically evaluating the various technical and experimental approaches used throughout the world to improve the species and/or size selectivity of fish trawls (and so reduce bycatch) via gear modifications. We then use this information to suggest a way forward for future work in this field.

Methods

Fish-trawl catching mechanisms

Any review of technical approaches to improve the selectivity of fishing gears first requires some overview of the associated catching mechanisms (McHugh et al. 2017). There are many different configurations of fish trawls, but like for other otter trawls, all adhere to a generic plan which can be separated into various zones according to the underlying catching process (McHugh et al. 2017; Melli et al. 2020; Fig. 1).

For the purposes of this review, and following previous definitions (e.g. McHugh et al. 2017), the first zone ('spreading mechanisms') includes the otter boards (or hydrovanes which are dragged along or very close to the seabed and angled so that they spread all of the rigging aft), sweeps (typically > 100 m) and bridles (Fig. 1). These non-netting components exploit the behavioural responses of most fish to herd them from the area in front of the entire trawl and into the netting components (Wardle 1989). The second zone can be defined as the entry point to the netting components and encompasses the weighted ground gear and foot rope (which keep the trawl on the seabed), and a headline with floats or kites that assist the mouth of the trawl to open vertically (Fig. 1). These zone-2 components are configured to stop the escape of fish under or over the trawl. Behind this rigging are the trawl wings and body (zone 3) which usually comprise sequentially smaller meshes, with the body following a long-tapered section designed to concentrate swimming and tiring fish towards their retention in the extension and codend. The latter is zone 4 and is usually not tapered, although the codend can have variable circumferences (within or between the extension) to accommodate catches.

Due to the size of the rigging involved in fish trawls, especially the lengths of sweeps, most configurations are towed as single rigs and only occasionally as twin (or 'dual') rigs comprising two outside otter boards and a centre weight or sled (e.g. Graham et al. 2003; O'Neill et al. 2006). Further, while there is considerable variability in fish-trawl designs within and among fisheries, in many cases the extension and codend are

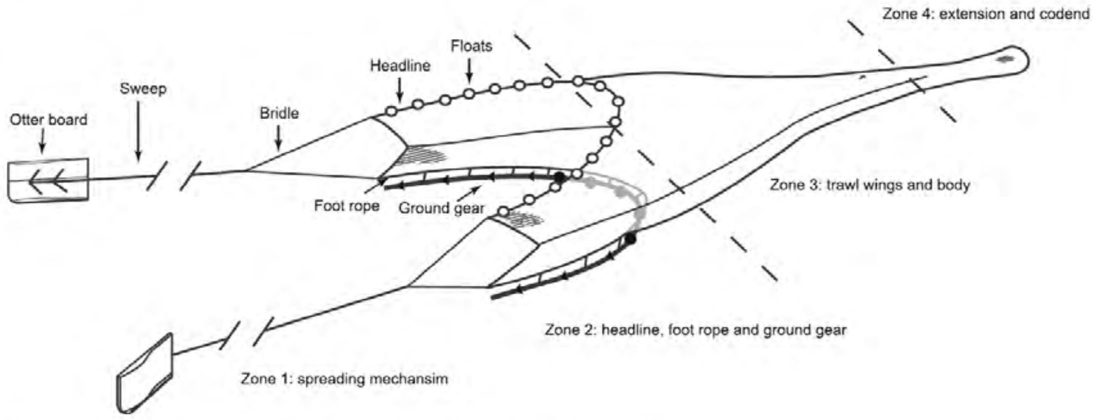

Fig. 1 A typical demersal otter trawl showing the four categorized zones

fairly homogenous, and are often the focus of input controls such as minimum mesh sizes due to the assumption that they are key areas affecting selection (Millar and Fryer 1999).

Scope of the review

This review focusses on empirical experiments done at sea to quantify modifications designed to improve the size or species selection of demersal otter trawls targeting fish (teleosts), and so excludes similar work with beam trawls or directed trawling for cephalopods, molluscs or crustaceans. Nevertheless, we acknowledge that at least some of these other species groups, and especially crustaceans, are retained and harvested as so-called 'by-product' in many fish-trawl fisheries (Kunjipalu et al. 2001; Aydin et al. 2014; Madhu et al. 2015; Brčić et al. 2018a, b).

Further, while there exist hundreds of national and international reports, magazine articles and other 'grey' literature describing research on modifications to fish trawls, this paper focusses only on papers in international, refereed journals. This approach ensures our critical consideration of the anonymously peer-reviewed empirical science used in this field. In any case, it was apparent that in many instances where modifications presented in the grey literature had merit, these were subsequently published in international journals. We also restricted our study to papers that were written in English.

Acquired material and synthesis

In this review, we followed a systematic approach with consideration to the 'preferred reporting items for systematic reviews and meta-analyses' (PRISMA) method (Liberati et al. 2009). To ensure the publications examined were as inclusive as possible, we began with ~ 150 papers describing experiments to test modified fish trawls gathered by us over the past 30 years. From these papers we derived 22 common words/phrases, including: 'selectivity', 'codend', 'square mesh', 'trawl,' 'grid', 'catch', 'bottom/demersal trawl', 'diamond mesh', 'bycatch reduction', 'square mesh', 'T0', 'T45', 'T90', 'discard', 'behaviour/behavior', 'twine', 'windows', 'multi-species', 'separating', 'ground gear', 'sweep' and 'twin trawl'. These terms and their combinations were incorporated into searches of the ISI Web of Science, Proquest and Google Scholar. We established an historical search window of January 1988 to October 2020, starting with the study by Robertson and Stewart (1988). The earliest boundary aligns with the findings of Millar (1992) and Millar and Walsh (1992) who detailed problems with the early analyses of selectivity studies involving paired-gear comparisons, and proposed a more rigorous approach (i.e. 'Share Each Length Catch Total' (SELECT) methodology) (Millar and Fryer 1999). While we do not comment on specific issues in papers prior to 1988, it became apparent that all useful earlier modifications were encapsulated in the later papers.

The search produced some 300 papers, which were then filtered and cross-referenced against our original 150. We excluded papers where fish were not the primary target, or those that did not investigate applied modifications to fishing gears at sea, such as theoretical or laboratory studies (for which there are many excellent works dating back to Sainsbury (1984) and more recently Tokaç et al. (2018)).

Papers that satisfied the search criteria were then examined in detail and partitioned into categories according to the four zones of the trawl in which they were focused (or combinations thereof), and whether the modifications were relatively 'simple' or 'complex' as described by Uhlmann and Broadhurst (2015). Specifically, simple modifications were those that were familiar to fishers and could be made within conventional configurations, including changes to: diamond-shaped mesh (also termed 'T0') simply by turning it 45° ('T45' by hanging it on the bar to make it 'square mesh') or 90° ('T90'); twine diameters; ground gears; or headline heights. We anticipated that such modifications might be more easily accepted by fishers than complex modifications, which extended beyond conventional configurations and involved often new (unfamiliar to fishers), retroactively fitted components such as separator panels, grids, light-emitting diodes or new trawl designs.

After categorising all papers, each was qualitatively summarized according to its defining characteristics. These included: where and when the study was done (including when the data were collected); up to six key target and bycatch species (the latter comprising either undersized targets and/or other species) and their general body type ('roundfish' that were fusiform or laterally compressed vs 'flatfish' that were dorsoventrally compressed); the specific modifications tested and the testing method (i.e. how modifications were assessed in trawls, along with ancillary equipment like net monitoring equipment or cameras); selectivity and/or efficiency improvements of modifications; and any stated or potential confounding/beneficial factors of the experimental designs or analyses (with reference to recommended approaches detailed in the literature, including Fryer 1991; Wileman et al. 1996; Millar and Fryer 1999).

Results

In total, 203 papers published in 36 journals and focussing on > 147 species across > 49 families satisfied the objectives of the search criteria (Tables 1 and 2). The journal Fisheries Research published 94 papers (i.e. 46% of the total), while a further 59 papers (29%) were distributed among seven journals: ICES Journal of Marine Science/Journal du Conseil (16 papers); Journal of Applied Ichthyology/Archive of Fishery and Marine Research (11); Scientia Marina (8); Aquatic living Resources (7); Turkish Journal of Fisheries and Aquatic Sciences (6); Fishery Technology (6); and the Canadian Journal of Fisheries and Aquatic Sciences (5).

Spatio-temporal patterns and species assessed

Most research (74%) to reduce fish-trawl bycatch has occurred in Europe (with 20% in the North Sea alone) (Fig. 2) and focused on haddock (*Melanogrammus aeglefinus* Gadidae), cod (*Gadus morhua* Gadidae), whiting (*Merlangius merlangus* Gadidae), hake (*Merluccius merluccius* Merlucciidae) and European plaice (*Pleuronectes platessa* Pleuronectidae)—species that were either individually or collectively assessed > 190 times in papers (Table 1). Other substantial European efforts have occurred in the Mediterranean Sea (particularly off Turkey and Italy) for multi-species fisheries, but often also with hake and/or red mullet (*Mullus barbatus* Mullidae), blue whiting (*Micromesistius poutassou* Gadidae), common pandora (*Pagellus erythrinus* Sparidae) and Atlantic horse mackerel (*Trachurus trachurus* Carangidae) (Table 1). Both round and flatfishes were often collectively assessed, but the former were the focus in four times more studies (79 vs 21%; Table 1).

Fewer papers (17%) were done off North America—despite extensive fish-trawl fisheries occurring there targeting cod and haddock, along with flatfish like American plaice (*Hippolossoides platessoides* Pleuronectidae); Pacific halibut (*Hippoglossus stenolepis*), various flounders and soles (Pleuronectidae) (Fig. 2). The remaining regions with multiple efforts were restricted to Australia (3%) and India (4%). There were no papers from South America and only one from each of Africa and Asia.

Irrespective of geographic location and species, 187 of the 203 papers described modifications within a

Table 1 Families and common and Latin names of species assessed in more than one published paper (January 1988 to October 2020) describing modifications to reduce bycatch in demersal fish trawls

Family	Common name	Latin name	No of papers
Anoplopomatidae	Sablefish	*Anoplopoma fimbria*	4
Bothidae[F]	Mediterranean scaldfish	*Arnoglossus laterna*	3
Callionymidae	Dragonets	*Callionymus* spp.	2
Carangidae	Atlantic horse mackerel	*Trachurus trachurus*	14
	Mediterranean horse mackerel	*Trachurus mediterraneus*	2
Gadidae	Silvery pout	*Gadiculus argenteus*	2
	Alaskan pollock	*Gadus chalcogrammus*	3
	Atlantic cod	*Gadus morhua*	59
	Haddock	*Melanogrammus aeglefinus*	64
	Whiting	*Merlangius merlangus*	24
	Blue whiting	*Micromesistius poutassou*	12
	Saithe	*Pollachius virens*	9
	Pouting	*Trisopterus luscus*	2
	Poorcod/Capelin	*Trisopterus minutus*	11
Hexagrammidae	Lingcod	*Ophiodon elongatus*	4
Leiognathidae	Ponyfish	*Leiognathus* sp.	2
Lophiidae	Blackbellied angler	*Lophius budegassa*	2
	Angler	*Lophius piscatorius*	5
Lotidae	Shore rockling	*Gaidropsarus mediterraneus*	2
Merlucciidae	Silver hake	*Merluccius bilinearis*	4
	European hake	*Merluccius merluccius*	33
	North Pacific hake	*Merluccius productus*	2
Moronidae	European seabass	*Dicentrarchus labrax*	2
Mullidae	Red mullet	*Mullus barbatus barbatus*	30
	Surmullet	*Mullus surmuletus*	6
	Goldband goatfish	*Upeneus moluccensis*	6
Nemipteridae	Randall's threadfin bream	*Nemipterus randalli*	3
Nephropidae	Norwegian lobster	*Nephrops norvegicus*	7
Pentanchidae	Blackmouth catshark	*Galeus melastomus*	3
Phycidae	Greater forkbeard	*Phycis blennoides*	6
Platycephalidae	Tiger flathead	*Neoplatycephalus richardsoni*	2
Pleuronectidae[F]	Arrow-tooth flounder	*Atheresthes stomias*	10
	Witch flounder	*Glyptocephalus cynoglossus*	2
	Rex sole	*Glyptocephalus zachirus*	4
	Flathead sole	*Hippoglossoides elassodon*	5
	Pacific halibut	*Hippoglossus stenolepis*	4
	American plaice	*Hippolossoides platessoides*	9
	Rock sole	*Lepidopsetta bilineata*	3
	Yellowfin sole	*Limanda aspera*	3
	Yellowtail flounder	*Limanda ferruginea*	5
	Common dab	*Limanda limanda*	3
	Lemon sole	*Microstomus kitt*	7
	Dover sole	*Microstomus pacificus*	11
	English sole	*Parophrys vetulus*	4

Table 1 continued

Family	Common name	Latin name	No of papers
	European flounder	*Platichthys flesus*	2
	European plaice	*Pleuronectes platessa*	15
	Winter flounder	*Pseudopleuronectes americanus*	3
	Common sole	*Solea solea*	2
Pomatomidae	Bluefish	*Pomatomus saltatrix*	2
Scophthalmidae[F]	Four-spot megrim	*Lepidorhombus boscii*	2
Scyliorhinidae	Lesser spotted dogfish	*Scyliorhinus canicula*	2
Sebastidae	Blackbelly rosefish	*Helicolenus dactylopterus*	2
	Widow rockfish	*Sebastes entomelas*	2
	Shortspine thornyhead	*Sebastolobus alascanus*	4
Sparidae	Bogue	*Boops boops*	2
	Annular seabream	*Diplodus annularis*	7
	Axillary seabream	*Pagellus acarne*	4
	Common pandora	*Pagellus erythrinus*	12
	Blotched picarel	*Spicara maena*	3
	Picarel	*Spicara smaris*	4
Synodontidae	Greater lizardfish	*Saurida tumbil*	2
	Brushtooth lizardfish	*Saurida undosquamis*	5
Trichiuridae	Largehead hairtail	*Trichiurus lepturus*	4
Zeidae	John dory	*Zeus faber*	3

[F]denotes flatfish

single zone of the trawl, with just 16 assessing modifications at multiple zones, including four papers describing modifications at all zones. Attempts at modifying each zone dated back to the earliest papers, but more recently there were clear temporal differences (Fig. 3). Efforts to address modifications within zones 1 (7% of the total), 2 (11%) and 3 (11%) remained temporally similar at averages of 0.4 to 0.7 studies year^{-1}. In contrast, cumulative efforts towards zone 4 (71% of the total) were substantially greater ($\sim$ 4.2 studies year^{-1}). Notwithstanding these differences, there has been a consistent trend towards simple, rather than complex modifications across all zones (Table 2, Fig. 3).

Experimental methodologies

In many papers, experimental methodologies were determined by the assessed zone and/or trawl configuration examined. Nevertheless, the basic approach involved at least one of three categories: (1) covers (over codends or escape exits, behind ground gears or as liners in codends); (2) alternate hauls (where treatments were deployed in sequences, usually by the same vessel); and/or (3) simultaneous paired comparisons, either by two vessels each towing a trawl side-by-side ('parallel haul'), one vessel towing paired trawls ('twin trawl'), or a single trawl with the codend split into side-by-side legs ('trouser trawl') (Wileman et al. 1996; Millar and Fryer 1999).

Reflecting the dominant focus of work on zone-4 modifications, the most common approach (104 papers or 51%) involved installing covers over the entire codend, and sometimes extension, to retain escaping fish. This approach was most prevalent in European fisheries. Cover designs varied but, to limit confounding effects, in many studies (like Campos and Fonseca 2003; Tosunoğlu et al. 2003) researchers followed the general recommendations of Wileman et al. (1996) with a mesh size approaching 50% of the

Table 2 Summary of the zone of the trawl, modifications assessed (and complexity) to improve selectivity, their impacts and reference(s)

Zone in trawl	Modification(s) and complexity	Impacts	Reference(s)
Zone 1 (spreading mechanisms)	Raising sweeps off the bottom (simple)	Reduced catches of some species (especially flatfish), but no major effects on sizes caught. Lowered sweeps had greater effect in daytime and raised sweeps had little effect at night	Rose et al. (2010), Ryer et al. (2010), Sistiaga et al. (2015), Lomeli et al. (2019)
	Changing warp, sweep or bridle lengths and angles (simple)	Longer warps, sweeps and bridles caught more. Catches of some small fish decreased with longer sweeps	Engås and Godø (1989b), Ramm et al. (1993), Lauth et al. (1998), Fiorentini et al. (1999), Somerton and Munro (2001), Somerton (2004), Sistiaga et al. (2016b)
	Changing spread ratio (simple)	Greater catches of all sizes with lower spread ratio	Rose and Nunnallee (1998)
Zone 2 (headline, foot rope and ground gear)	Long, cutaway headropes (including the 'topless trawl') (complex). Lowering the headline (simple)	Reduced catches of unwanted sizes of certain species, especially roundfish, but less so for flatfish. Lower headline reduced catches of cod but maintained catches of flatfish	Thomsen (1993), King et al. (2004), Hannah et al. (2005), Chosid et al. (2008), Krag et al. (2015), Eayrs et al. (2017), Earys et al. (2020)
	Raising foot rope using floats, weights, spokes, rubber discs and/or wide spacing of discs (simple)	Reduced bycatches of unwanted fish and benthic infauna	Engås and Godø (1989a), Ramm et al. (1993), Brewer et al. (1996), Dahm (2000), Guyonnet et al. (2008), Krag et al. (2010)
	Rockhopper, 'semicircular spreading ground gear (SCSG)' and alternate light (rubber) ground gears (complex)	The SCSG caught more larger fish. Lighter ground gear caught less overall	Brinkhof et al. (2017), Lauth et al. (1998), Larsen et al. (2018a)
	Rollers or large rubber discs on ground gear or with/without tickler chains (simple)	Discs increased catches of flatfish and reduced catches of cod. Rollers decreased catches of invertebrates and debris with some reduction in smaller sizes of targets. Removing a tickler chain reduced catches of unwanted elasmobranchs but also targeted flatfish	Ball et al. (2003), Reid et al. (2012), Kynoch et al. (2015)
	Light emitting diodes or fibre-optic lights along headline or foot rope (complex)	Variable, but some species-specific changes in behaviour at night	Lomeli et al. (2018), O'Neill and Summerbell (2019)
Zone 3 (trawl wings and body)	Increase mesh size throughout conventional T0 netting (simple)	Reduced catches of unwanted sizes of certain species, while maintaining target catches	Broadhurst and Kennelly (1995), Beutel et al. (2008), Campbell et al. (2010), Kynoch et al. (2011)
	Horizontal separator panels/frames in the trawl; some from the headline through to extension (complex)	Good at separating species with different vertical orientations (e.g. cod and haddock)	Cotter et al. (1997), Engås et al. (1998), Ferro et al. (2007), He et al. (2008, Holst et al. (2009), Krag et al. (2009), Park et al. (2012)
	Windows in various parts of trawl body (simple); some with guiding panels (complex)	Reduced catches of unwanted sizes while maintaining target catches; especially for flatfish depending on location of panel	Ball et al. (2003), Milliken and DeAlteris (2004), Madsen et al (2006), Bayse et al. (2016), Santos et al. (2016b), Bonanomi et al. (2020)

Table 2 continued

Zone in trawl	Modification(s) and complexity	Impacts	Reference(s)
Zone 4 (extension and codend)	Increase codend mesh size throughout conventional T0 netting (simple)	Increasing T0 mesh size typically improved L_{50}s across comparable, but sometimes with increased and/or variable SRs	Reeves et al. (1992), Broadhurst and Kennelly (1995), Galbraith et al. (1994), Perez-Comas et al. (1998), Campos and Fonseca (2003), Campos et al. (2003), Tosunoğlu et al. (2008), Joksimovic et al. (2009), Sala and Lucchetti (2011), Hunt et al. (2014), Wienbeck et al. (2014), Madhu et al. (2015), Pol et al. (2016a, 2016b)
	Different codend circumferences and lengths (simple). Single vs double codends (simple)	Smaller codend diameters and lengths increased L_{50}s with usually minimal effects (or a slight increase) on SRs for T0 codends. Single codends also had higher L_{50}s than double, with similar SRs	Reeves et al. (1992), Galbraith et al. (1994), Özbilgin and Tosunoğlu (2003), Tosunoğlu et al. (2003), Özbilgin et al. (2005), O'Neill et al. (2008), Graham et al. (2009), Sala and Lucchetti (2011), Wienbeck et al. (2011), Eryasar et al. (2014), Herrmann et al. (2015a), Sala et al. (2016), Demirci et al. (2017), Ilkyaz et al. (2017), Veiga-Malta et al. (2019)
	Different codend twine materials, thickness (including single vs double), colour and flexibility (simple)	Thinner, single and more flexible twine increased L_{50}s with reduced or unchanged SR. Colour had no effect. Similar effects for Dyneema and slight improvements for polyamide twines. No effects of knotless twine	Lowry and Robertson (1996), Madsen et al. (1998), Kynoch et al. (1999), Tokaç et al. (2004), Sala et al. (2007), Graham et al. (2009), Herrmann et al. (2013a), O'Neill et al. (2016), Cheng et al. (2019)
	Removing or changing strengthening bags, chafing gear, or lastridge ropes (simple)	Strengthening bags/chafing gear or increasing their circumference had variable effects on L_{50} and SR. In some studies L_{50} was decreased or unchanged with increases in SR, but in some L_{50} increased with no effect on SR. Shortening/removing lastridge ropes had similar variable effects	Lök et al. (1997), Dahm (1998), Halliday and Cooper (2000), Tosunoğlu et al. (2003), Kynoch et al. (2004), Aydin et al. (2014), Demirci et al. (2019)
	T45 mesh codends instead of T0 (simple)	T45 meshes in codends usually reduced SRs across comparable L_{50}s as similar-sized T0 meshes for roundfish, but less so for flatfish	Robertson and Stewart (1988), Millar and Walsh (1992), Walsh et al. (1992), Wallace et al. (1996), Petrakis and Stergiou (1997), Stergiou et al. (1997), Dahm (1998), Perez-Comas et al. (1998), Tokaç et al. (1998), Halliday et al. (1999), Stergiou (1999), Halliday and Cooper (2000), Kunjipalu et al. (2001), Campos and Fonseca (2003), Campos et al. (2003), Bahamon et al. (2006), Ordines et al. (2006), Sardá et al. (2006), He (2007), Lucchetti (2008), Prakash et al. (2008, 2013), Sala et al. (2008), Ateş et al. (2010), Aydin et al. (2011), Özbilgin et al. (2012, 2015), Rajeswari et al. (2013), Tokaç et al. (2014), Dereli and Aydin (2016), Madhu et al. (2016), Düzbastilar et al. (2017), Demirci and Akyurt (2017), Brčić et al. (2018b), Joshy et al. (2018), Ceylan and Sahin (2019), Eryasar and Özbilgin (2015), Zengin et al. (2019)

Table 2 continued

Zone in trawl	Modification(s) and complexity	Impacts	Reference(s)
	T90 or hexagonal-mesh codends instead of T0 (simple)	T90 usually increased L_{50}s with reduced or unchanged SRs for similar T0 mesh sizes; but less so for flatfishes. Hexagonal mesh similarly affected the size selection of Atlantic horse mackerel	Kunjipalu et al. (1994), Moderhak (1997), Moderhak (1999), Moderhak (2000), Aydin and Tosunoglu (2010), Digre et al. (2010), Wienbeck et al. (2011), Herrmann et al. (2013a), Dereli and Aydin (2016), Ilkyaz et al. (2017), Lomeli et al. (2017a), Kaykaç et al. (2018), Veiga-Malta et al. (2019)
	T45 or T0 windows in conventional codends (simple)	T45 windows usually increased L_{50}s with reduced or at least unchanged SRs, especially for round fish. T0 windows also similarly improved selectivity for some species	Moderhak (2000), Zuur et al. (2001), Madsen et al. (2002), Metin et al. (2005), Özbilgin et al. (2005), Madsen et al (2006), Bullough et al. (2007), Grimaldo et al. (2007), Kaykaç (2010), Tokaç et al. (2010), Özdemir et al. (2012, 2014), Wienbeck et al. (2014), Alzorriz et al. (2016), Sistiaga et al. (2018), Ceylan and Sahin (2019)
	Positioning of T0/T45/T90 panels/windows/cylinders in extensions and codends (simple)	Moving T45 windows aft improved L_{50}s with reduced or unchanged SRs. Having windows on the top of the codend was usually better than on the sides, but for some species having panels on the bottom was better. Having T45 or T90 as a full cylinder in the extension improved L_{50}s while maintaining SRs for some species	Graham and Kynoch (2001), Graham et al. (2003), Madsen and Staehr (2005), O'Neill et al. (2006), Herrmann et al. (2015b), Brčić et al. (2016,2018a), Kopp et al. (2018), Sola and Maynou (2018), Ceylan and Sahin (2019), Mouchet et al. (2019), Cuende et al. (2020b)
	Assessment of stimulation/guiding devices inside codend and/or extension to direct fish to escape panels/windows (complex)	Reduction in catches of most unwanted species with little loss of targets. Inserting solid black panels in codends evoked some behavioural responses, but LEDs had few effects	Glass and Wardle (1995), He et al., (2008), Lomeli and Wakefield (2012), Herrmann et al. (2015b), Fraser and Angus (2019), Cuende et al. (2020a, 2020b)
	Size-selective grids, including the sort-X, sort-V, FRESWIND or flexi-grids (rigid or flexible) (complex)	Mostly reduced SR for any required L_{50}. Angles of grids affected selectivity. Few diurnal effects. Main advantage of flexible grids is ease of handling	Larsen and Isaksen (1993), Rose (1999), Sardá et al. (2004, 2005, 2006), Jørgensen et al. (2006), Bahamon et al. (2007), Aydin et al. (2008), Herrmann et al. (2013b), Larsen et al. (2016), Santos et al. (2016a), Özvarol (2016a, 2016b), Gamaza et al. (2018), Larsen et al. (2018b), Brinkhof et al. (2020), O'Neill et al. (2008), Sistiaga et al. (2009, 2016a, 2018).

Table 2 continued

Zone in trawl	Modification(s) and complexity	Impacts	Reference(s)
	Species-selective grids, including the Nordmøre or super-shooter grids (rigid or flexible) (complex)	Reduced key megafauna by up to 100%, with no loss of targeted fish. Main advantage of flexible grids is ease of handling	Chosid et al. (2012), Eigaard et al. (2012), Brčić et al. (2015), Lomeli and Wakefield (2013, 2016), Lucchetti et al. (2016), Lomeli et al. (2017b), Vasapollo et al. (2019)
	Assessment of certain lifting/guiding panels/funnels/deflectors to direct fish (complex)	Significantly improved selectivity (i.e. increased L_{50}s with reduced or constant SRs).in most studies and for many species	Halliday and Cooper (1999), Rose and Gauvin (2000), Maartens et al. (2002), Kvamme and Isaksen (2004), Kvalsvik et al. (2006), Sistiaga et al. (2008, 2009, 2012), Herrmann et al. (2013c), Grimaldo et al. (2015)
	Combinations of grids and T0/T45 mesh windows (complex)	Improved L_{50}s with reduced or constant SRs for most species examined	Eigaard and Holst (2004), Graham et al. (2004a, b), Fonseca et al. (2005), Coll et al. (2008), Grimaldo et al. (2008, 2009), Wakefield et al. (2017), Vogel et al. (2017), Herrmann et al. (2019)
	Mechanisms to release fish at certain depths or when catches reach a certain level using acoustic releases, weak-links or pre-set holes (complex)	Expensive and complex systems that did not seem to perform better than other modifications	Grimaldo et al. (2014), Brinkhof et al. (2019)
Other modifications	Comparisons of trawls, often modified with different sweep and bridle lengths, headline heights, floats, ground chains, and/or mesh sizes in various parts of the wings, body and codend (complex)	Significant species-specific differences due to modified trawls, but causes are often difficult to determine due to combinations of modifications within each	Fiorentini et al. (1999), Cartes et al. (2009), Holst and Revill (2009), Reid et al. (2012), Manjarres-Martinez et al. (2015)
	Single vs twin trawls (simple)	Standardized catches of some species were greater in twin gear	Sangster and Breen (1998)
	Overall size of gear (simple)	No effects of total net size on standardized catches	Dahm et al. (2002)

T0, diamond shaped; T45, square shaped; T90, turned 90°

Fig. 2 Map showing the locations and numbers of studies assessing technical modifications to demersal otter trawls targeting fish during 1988 to 2020

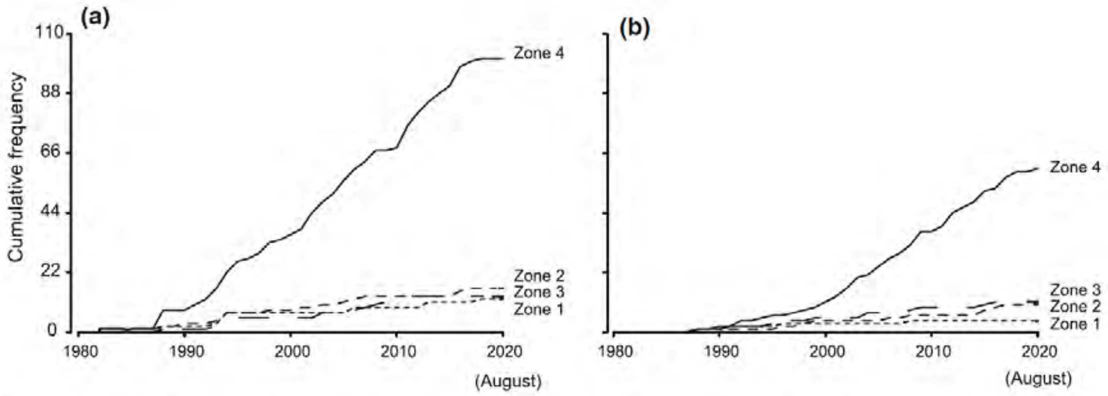

Fig. 3 Cumulative frequency of papers through time (1988 to 2020) describing **a** simple and **b** complex modifications to the defined four zones of demersal fish trawls

smallest treatment, and hooped circumferences and lengths 1.5 and 2.0 times the largest treatment codend. Nevertheless, very few studies (e.g. Madsen et al. 2002) formally tested for confounding effects as described by Madsen and Holst (2002), although cameras were sometimes used (Campos and Fonseca 2003; Kvalsvik et al. 2006).

Smaller covers were used over the escape exits of several zone-4 modifications (Zuur et al. 2001; Maartens et al. 2002; Sistiaga et al. 2010, 2016a; Herrmann et al. 2013c; Aydin et al. 2014; Ceylan and Sahin 2019; Brinkhof et al. 2020), or on their own (Eigaard and Holst 2004; Sardá et al. 2005, 2006; Aydin et al. 2008; Eigaard et al. 2012) and/or with small-mesh codend liners (Larsen and Isaksen 1993; Maartens et al. 2002; Sistiaga et al. 2016a, 2018; Mouchet et al. 2019). Typically, a covered treatment was assessed in isolation, and without concomitant were usually done over a greater number of replicate deployments, reflecting the likelihood of increased between-haul variability. Specifically, alternate-haul experiments nearly always involved at least 10 to 30 replicate tows of individual trawls (Galbraith et al. 1994; Eayrs et al. 2017,2020; Fraser and Angus 2019; Lomeli et al. 2019) up to > 80 (Bullough et al. 2007), while paired-comparison approaches had between 5 and 40 replicates (Graham et al. 2003; Graham et al. 2004a, b; Madsen and Staehr 2005; Veiga-Malta et al. 2019; Krag et al. 2009; Kynoch et al. 2011; Campbell et al. 2010; Bonanomi et al. 2020), but as many as 100 (Beutel et al. 2008). Similar detail required in analyses has meant that, as for covered codends, data collected during the same paired-comparison cruises appear to have sometimes been presented in separate papers (e.g. Pol et al. 2016a, 2016b).

More recently, where small-meshed controls were not used in alternate-haul or paired-gear comparisons, but rather treatments were compared against conventional gears, relative selectivity estimates have been made via catch comparisons described by Holst and Revill (2009) and others (e.g. Krag et al. 2015). These approaches produce model estimates of the expected proportions of fish at size and catch ratios in the treatment trawl (Eryasar and Özbilgin 2015; Lomeli et al. 2018, 2019; Fraser and Angus 2019). Also, unlike covered-codend studies, in some cases (mostly off North America and Australia) broader categories of catch data (numbers and weights of species) from alternate-haul or paired-gear comparisons in multi-species fisheries have been analysed using linear (often mixed) models or ANOVA (Brewer et al. 1996; Rose and Nunnallee 1998; Hannah et al. 2005; Graham et al. 2009), and very occasionally simple t-tests or non-parametric approaches (King et al. 2004; Milliken and DeAlteris 2004). These approaches produced mean percentage reductions of bycatch species or unwanted sizes.

Zone-specific modifications

Irrespective of the methodological approach, each of the four zones in the trawl were subjected to various modifications (often with more than one assessed in a particular study) designed to exploit either the perceived behavioural responses and swimming capacities of the key species (especially zones 1 to 3), their sizes (especially zone 4) and/or their morphology (i.e. round vs flatfish) (Table 2). And because researchers are unlikely to publish null results, in all papers at least some aspects of the assessed modification(s) explained variability in the catches of focal species; albeit with substantial variations of influences. Reflecting the work done in each zone, modifications increased in diversity from the anterior to the posterior of the trawl (Table 2).

Zone 1 (spreading mechanisms)

The relatively few attempts at modifying spreading mechanisms were mostly simple, unless as part of changes to other zones (where 50% of modifications were complex) and designed to mostly exploit broad inter-specific behavioural differences (Fig. 3; Table 2). Within the former, variable warp, sweep or bridle lengths were common and often showed quite strong positive and negative impacts on catches of larger and smaller species, respectively (e.g. Engås and Godø 1989b; Sistiaga et al. 2016b). Simply raising sweeps off the bottom decreased the catches of some species (especially flatfish, Pleuronectidae), and often with greater impacts during daylight, while maintaining target catches (Rose et al. 2010; Ryer et al. 2010; Sistiaga et al. 2015; Lomeli et al. 2019) (Table 2). As for penaeid trawls (McHugh et al. 2017), optimising spread ratio for specific designs of fish trawls is important and was clearly illustrated by Rose and Nunnallee (1998) who observed greater catches of arrowtooth flounder (*Atheresthes stomias*, Pleuronectidae), flathead sole (*Hippoglossoides elassodon*, Pleuronectidae) and Alaskan pollock (*Gadus chalcogrammus*, Gadidae) as spread ratio decreased (via a constraining line) in Alaskan trawls.

Zone 2 (headline, foot rope and ground gear)

Modifications at the headline, foot rope and ground gear, whilst also few in number, improved trawl selectivity and/or efficiency for both round (e.g. haddock and cod) and flatfish (flounder, *Platichthys flesus* Pleuronectidae, plaice and dover sole, *Microstomus pacificus* Pleuronectidae) via behavioural mechanisms and also reduced benthic infauna and debris in the trawl (Table 2). Of particular note were improvements generated by using relatively longer (cutaway) headropes (including the 'topless trawl'; Chosid et al. 2008) which were designed to exploit the testing of a conventional configuration (e.g. Metin et al. 2005; Park et al. 2012; Lomeli and Wakefield 2016; Larsen et al. 2016, 2018b). Other covers or collecting bags were occasionally used in zone-2 or -3 modifications to retain organisms escaping under the foot rope/ground gear (Pol et al. 2016b; Kaykaç et al. 2018) or through anterior trawl panels (Park et al. 2012; Santos et al. 2016b; Larsen et al. 2018a).

Data describing catch-at-length for individual species were collected from the codend and cover and typically analysed using various parametric selection curves via maximum likelihood to produce parameter vectors of interest, including the 50% size at selection (L_{50}) and selection range (SR; defined as 70% size at selection—25% size at selection). Such analyses usually incorporated between-haul variation (Fryer 1991) and assessments of model fits (discussed by Millar and Fryer 1999), but not always (Rose 1999; Sardá et al. 2004; Prakash et al. 2013; Rajeswari et al. 2013). Occasionally, additional fixed effects like catch weight (O'Neill et al. 2016) or towing speed (Sala et al 2007) were included in models, and often with variable effects. Any stated selectivity improvements by modified vs conventional configurations were mostly based on either maintaining or increasing L_{50} with a reduced SR, or a constant SR but improved L_{50}. In recent years, several cases of more complex models were used to partition estimated selectivity parameters among different modifications in codend/extensions, and so provide greater detail about the relative efficacy of components (e.g. Sistiaga et al. 2010, 2018; Herrmann et al. 2013c; Brinkhof et al. 2020).

Due to the analyses involved, using covers typically means that studies done in multi-species fisheries have selectivity assessments limited to fewer than seven or eight species (He 2007; Özbilgin et al. 2015; Özvarol 2016b; Brčić et al. 2018a; Kopp et al. 2018), but often only one (e.g. Lowry and Robertson 1996; Moderhak 1997, 1999, 2000; Kynoch et al. 2004; Özvarol 2016a) or two (Reeves et al. 1992; Larsen and Isaksen 1993; Grimaldo et al. 2009; Larsen et al. 2018a, b), or even precipitated separate papers based on data from the same cruise but for different species (Özvarol 2016a, b; Larsen et al. 2016, 2018b) or analyses (Demirci et al. 2017; Cuende et al. 2020a; Brčić et al. 2016, 2018a). The numbers of replicate deployments among treatments have varied considerably, with many involving between 10 and 30 (Kynoch et al. 1999; Campos and Fonseca 2003; Bahamon et al. 2006; Ateş et al. 2010; Krag et al. 2010; Demirci and Akyurt 2017), but some were as low as two (Moderhak 1997; Özdemir et al. 2012; Herrmann et al. 2013c) and as high as 60 or 70 (Gamaza et al. 2018; Campos et al. 2003).

Alternate-haul approaches were presented in 45 papers (22%), and often where treatment trawls encompassing zone 1–3 modifications were compared against control (unmodified) trawls in single-rigged fisheries (e.g. Ramm et al. 1993; Madsen et al. 2006; Grimaldo et al. 2015; Sola and Maynou 2018). Alternate hauls were also used for testing various zone-4 modifications and, in contrast to cover-based experimental designs, were more popular among non-European fisheries (e.g. Wallace et al. 1996; Perez-Comas et al. 1998; He et al. 2008; Graham et al. 2009; Chosid et al. 2012; Wakefield et al. 2017). In some papers assessing zone 1–3 changes, alternate hauls were complemented with ancillary equipment, including trawl-monitoring gear to account for variable spread ratios (defined as the wing-end spread divided by the headline length; e.g. Lauth et al. 1998; Somerton 2004; Lucchetti et al. 2016) and therefore headline height, or cameras (Glass and Wardle 1995; Ferro et al. 2007; He et al. 2008; Wakefield et al. 2017); but not always (Broadhurst and Kennelly 1995; Manjarres-Martinez et al. 2015). Simultaneous paired comparisons were only slightly less common (in 36 papers) and also popular in non-European fisheries, with nine involving trouser trawls (e.g. Millar and Walsh 1992; Pol et al. 2016a), 21 with twin trawls (e.g. Cotter et al. 1997; Graham et al. 2004a, b) and six using parallel hauls (e.g. Pol et al. 2016a, b). Paired comparisons were used to assess modifications across all zones and, as for alternate hauls, often used with ancillary techniques to validate consistent inter-trawl geometries (Pol et al. 2016a, b; Reid et al. 2012; Krag et al. 2015).

Where a small-meshed control codend was used in alternate-haul or simultaneous paired-comparison approaches, catch-at-length data were similarly analysed for parametric selection curves as above for covered approaches, but usually accounting for different probabilities of retention in the treatment and control gears (e.g. via the SELECT method; Halliday et al. 1999; Sistiaga et al. 2008). Additional fixed factors such as catch weight were also occasionally modelled (O'Neill et al. 2006; Pol et al. 2016a, 2016b). However, unlike covered codend work, assessments behavioural response of fish that rise up and increased the escape of haddock, but less so for flatfish (Thomsen 1993; King et al. 2004; Hannah et al. 2005; Eayrs et al. 2017). Similarly, Eayrs et al. (2020) showed that lowering the headline significantly decreased cod catches by a substantial amount (but not flatfish).

Other common zone-2 modifications involving raising the foot rope and other changes to ground gears have mostly maintained target catches, while reducing bycatches of several roundfish including, but not limited to, lutjanids (Brewer et al. 1996), grey gurnard (*Eutrigla gurnardus* Triglidae), whiting, saithe (*Pollachius virens* Gadidae) and Atlantic horse mackerel (Dahm 2000). Such modifications have also reduced the amounts of debris and benthic infauna caught (Ramm et al. 1993; Rose and Nunnallee 1998; Krag et al. 2010). In particular, several studies have compared rockhopper ground gear with alternatives, including the so-called 'semicircular spreading ground gear' which improved catching efficiency for larger cod and haddock, while reducing drag (Brinkhof et al. 2017; Larsen et al. 2018a). Other, simpler, modifications to ground gear have involved exploiting species-specific responses to herding stimuli. For example, Kynoch et al. (2015) demonstrated that removing tickler chains reduced catches of elasmobranchs without affecting targeted haddock, whiting and flatfish. The utility of light emitting diodes (LEDs) as stimuli for exploiting behaviour in zone 2 was tested in some studies with variable selectivity improvements, although, not surprisingly, greater nocturnal effects for certain species (Lomeli et al. 2018; O'Neill and Summerbell 2019).

Zone 3 (trawl wings and body)

Within this anterior-netted section, simply increasing lateral-mesh openings via larger T0 mesh towards the tapering end to match the desired sizes of target species generally improved size selection for roundfish, mostly maintaining commercial catches while reducing unwanted sizes of species such as haddock, whiting and devil anglerfish (Beutel et al. 2008; Holst and Revill 2009; Campbell et al. 2010; Kynoch et al. 2011) (Table 2). A particularly successful suite of modifications has involved horizontal separator panels throughout the trawl to separate downwards-orientating (cod and most flatfish) from upwards-rising species (haddock, whiting and saithe), with possibilities for better selectivity via other compartment-specific modifications in either the trawl body or codend (Cotter et al. 1997; Engås et al. 1998; Ferro et al. 2007; Holst et al. 2009). Short horizontal panels restricted to the aft section of the trawl body also appear to have utility (He et al. 2008). Horizontal separator panels have also extended towards directing jellyfish (Scyphozoa) from trawls through escape exits; albeit with some loss of targeted fish (Park et al. 2012).

Zone-3 modifications have also included various lateral or top-orientated 'windows' in the trawl body made from either T0 or T45 mesh, with some extending throughout (Ball et al. 2003; Bayse et al. 2016; Bonanomi et al. 2020). Generally, the utility of these windows has reflected not only the behaviour of key species but also their shape, with flatfishes better suited to escaping through T0 than T45 meshes (Milliken and DeAlteris 2004). Most designs have reduced unwanted sizes, although it is clear lateral-mesh openings need to be carefully considered in multi-species fisheries to avoid loss of targets (Bonanomi et al. 2020).

Zone 4 (extension and codend)

Based on the long-standing assumption that the codend is responsible for most of the selection in a trawl (Millar and Fryer 1999), the earliest modifications tested to improve fish-trawl size selectivity involved simply increasing the conventional T0 mesh (e.g. Walsh et al. 1992). Such changes are described in 14 papers (Table 2) and, because many fisheries initially had mesh sizes chosen by industry prior to being regulated (and were therefore as small as possible), in virtually all cases these changes led to increases in L_{50}s, often with reasonable SRs and therefore maintained target catches commiserate with expectations.

Some studies concurrently investigated changes in codend configurations other than increasing mesh size. For example, reducing the circumferences of codends and/or the lengths of extensions improved selectivity for various species for T0 mesh codends (described in 15 papers including very good studies by Wienbeck et al. 2011; Eryasar et al. 2014; Herrmann et al. 2015a). The codend material also had effects, whereby single and more flexible twine often improved selectivity (in nine papers and particularly those by Kynoch et al. 1999; Sala et al. 2007); however variable twine diameters were sometimes overlooked in some zone-4 studies assessing other factors (Lowry and Robertson 1996; O'Neill et al. 2016). Also, removing external rigging like strengthening bags and chafing gear, or even increasing their circumferences improved selectivity in seven papers including those by Tosunoğlu et al. (2003), Kynoch et al. (2004) and Demirci et al. (2019).

But the largest number of studies done to improve selectivity in fish trawls has involved simply replacing T0 with T45 mesh throughout codends (38 papers including very good experiments by Robertson and Stewart 1988; Millar and Walsh 1992; Halliday et al. 1999; He 2007; Lucchetti 2008; Özbilgin et al. 2012; Tokaç et al. 2014; Düzbastilar et al. 2017; Demirci and Akyurt 2017) (Table 2). Various configurations of T45 codends have been assessed in many fisheries, across many species assemblages and with a general trend of facilitating either maintained or improved L_{50}s across lower SRs for roundfish, including Atlantic horse mackerel (Campos et al. 2003), red mullet (Dereli and Aydin 2016), hake (Halliday and Cooper 2000), cod (Halliday et al. 1999; He 2007), haddock and saithe (Halliday et al. 1999), Dussumier's anchovy (*Thryssa dussumieri* Engraulidae Madhu et al. 2016; Joshy et al. 2018) and largehead hairtail (*Trichiurus lepturus*, Trichiuridae; Rajeswari et al. 2013). While codends made from T45 mesh can also have lower SRs than the same-sized T0 mesh for flatfish (e.g. American plaice; Millar and Walsh 1992; Walsh et al. 1992), generally they are less effective at improving their size selection (Wallace et al. 1996; Perez-Comas et al. 1998).

One recurring issue with T45 codends is their relatively lower netting flexibility and strength than T0 codends (Madsen 2007). These deficits have been addressed in some fisheries by simply turning meshes to 90°, effectively increasing and maintaining lateral-mesh openings which can produce similar selectivity across comparable mesh sizes as T45. Codends made entirely of T90 mesh first appeared in 1997 in the Baltic Sea (Moderhak 1997, 1999, 2000) and have subsequently been assessed in 13 papers (all in Europe except for Lomeli et al. 2017a) including detailed studies for cod, European plaice and red mullet by Wienbeck et al. (2011) and Kaykaç et al. (2018). We also located a single study examining hexagonal mesh, but the authors noted fewer benefits in terms of maintaining SR and increasing L_{50} than the same sized T45 mesh (Aydin and Tosunoglu 2010).

In addition to codends made entirely of alternative meshes, many studies assessed the effects and positioning of various windows made from larger T0 or T45 mesh, which have the advantage of only altering a small section of conventional codends and so maintaining many existing operational characteristics (Table 2). Generally, such windows allowed unwanted sizes or species to escape with few impacts on commercial catches and tended to function better the further aft they were positioned in the codend for several species, including haddock (Graham and Kynoch 2001; Graham et al. 2003; O'Neill et al. 2006) and cod (Herrmann et al. 2015b), but sometimes not for whiting (Graham et al. 2003). The use of guiding/stimulating devices in the codend to herd fish towards such windows where they can then be selected based on size further improved effectiveness in some cases (e.g. for cod; Fraser and Angus 2019), although LED lights seem to have little effect on the few assessed species, including hake and whiting (Cuende et al. 2020a, b).

As well as simple changes to lateral-mesh openings in the codend and/or extension, many studies have examined complex modifications including grids (with and without guiding panels and deflectors) to similarly exclude either (1) different sizes of the target species ('size-selective' grids); or (2) much larger organisms ('species-selective' grids). Both categories have been tested across many jurisdictions, but most work occurred with size-selective designs in the Barents and North seas in attempts at increasing or maintaining L_{50}s, while reducing SR for a few key species (Table 2).

Among the early size-selective grids was the 'sort-X' (Larsen and Isaksen 1993); a steel grid made in three sections with 55-mm bar spaces that was first tested in the North Sea with cod and haddock and then other fisheries (Sardá et al. 2004; Herrmann et al. 2013b; Gamaza et al. 2018). The sort-X improved selectivity for cod and haddock in several studies. Other authors tested variations of the sort-X concept with variations being the single steel, 'sort-V' (Kvamme and Isaksen 2004; Jørgensen et al. 2006; Sistiaga et al. 2008, 2010; Herrmann et al. 2013c), FRESWIND (Santos et al. 2016a) and the more commonly used plastic and fibreglass 'flexi-grids'

(Sistiaga et al. 2009, 2016a; Brinkhof et al. 2020) which, subject to determining appropriate bar spaces (Sistiaga et al. 2008; Herrmann et al. 2013c; Vogel et al. 2017) generally reduced SRs and so improved selectivities in the fishery(ies) examined, and with easier handling than the sort-X. However, SRs have remained sufficiently wide to evoke substantial loss of target sizes in fisheries seeking to reduce all undersized catches (Brinkhof et al. 2020). Further, at least some work has demonstrated similar selectivity being achieved though simpler modifications, like windows with greater/more consistent lateral-mesh openings; albeit with variable differences in the timings of escape (e.g. Grimaldo et al. 2008). In particular, Jørgensen et al. (2006) noted few differences for cod between the sort-V and simply increasing codend mesh size.

Following their widespread use and success in penaeid trawls (Broadhurst 2000), species-selective grids, including the Nordmøre-, super-shooter and other top- or bottom-opening, inclined grids have been tested in some fish trawls (Chosid et al. 2012; Lomeli and Wakefield 2013, 2016; Brčić et al. 2015), some with various types of lifting/guiding panels and/or funnels to direct fish (e.g. Halliday and Cooper 1999; Rose and Gauvin 2000; Grimaldo et al. 2015). Their consideration was mainly precipitated by a need to reduce bycatches of charismatic megafauna, including sea turtles (Vasapollo et al. 2019), elasmobranchs (Chosid et al. 2012; Brčić et al. 2015) and marine mammals (Wakefield et al. 2017). Providing bar spaces were sufficient, several designs have successfully maintained target catches (but see Brčić et al. 2015) while reducing megafauna by close to 100%.

There have also been several studies that have examined combinations of grids with T0/T45 mesh windows (Eigaard and Holst 2004; Graham et al. 2004a, b; Fonseca et al. 2005; Grimaldo et al. 2008, 2009; Herrmann et al. 2019). Most have proven to be quite successful at improving L50s at reduced or constant SRs.

A final suite of quite complex and expensive modifications to zone 4 involve mechanisms to release fish at certain depths or when catches reach a certain level using acoustic releases, weak-links or pre-set holes in the codend/extension (Grimaldo et al. 2014; Brinkhof et al. 2019). While they do have fishery-specific utility for ensuring quotas of target species are not exceeded, in terms of reducing unwanted bycatches more broadly, such modifications might not perform better than other, simpler approaches.

Other modifications

Sixteen papers simultaneously examined combinations of simple and complex modifications within more than one zone in the trawl. For some studies, the individual utility of some modifications could be deciphered and were included in the relevant zones discussed above, although some experimental designs precluded completely understanding which components were responsible for improving selectivity and/or efficiencies (e.g. Fiorentini et al. 1999; Madsen et al. 2006; Cartes et al. 2009; Manjarres-Martinez et al. 2015). Seven papers, including four assessing all zones in the trawl, were not partitioned above and are included here because they mostly comprised completely different trawls which were typically assessed during surveys (e.g. Cartes et al. 2009; Reid et al. 2012; Manjarres-Martinez et al. 2015). The exceptions were Sangster and Breen (1998) who compared single and twin rigs and showed that standardised (for swept area) catches of some species were greater in twin gear, and Dahm et al. (2002) who compared different sizes of trawls and showed no effect on standardized catches.

Discussion

The problem unresolved

The reviewed 203 papers describe some 28 broad categories of simple and complex technical modifications for improving size or species selectivity, and so reducing unwanted bycatches in fish trawls over the past three decades. However, despite these options, no fishery has completely resolved all bycatch problems while maintaining targeted catches at conventional levels. And nor is this likely to occur—because the generic design of trawls, the different behaviours, sizes and shapes of fish caught, combined with diverse, and ever-changing priorities regarding target species (and therefore bycatches) preclude absolute 100% selectivity in such gears (and, indeed, for most fishing gears—Kennelly and Broadhurst 2002).

The effect of the above issues is clearly evident in the many papers and, indeed, overarching bias in research efforts in this field towards relatively few species—particularly the 64 and 59 papers focussing on haddock and cod, respectively (with 15 in the most recent two years). Some justification for this historical focus can be attributed to variable minimum legal sizes among fisheries, such as 32 (Madsen and Staehr 2005), 35 (Moderhak 1999), 38 (Santos et al. 2016a), 44 (Sistiaga et al. 2015) and 47 cm TL (Sistiaga et al. 2008) for cod, and inconsistent relationships between L_{50} and SR affecting the consistency of scaled-up modifications (Wileman et al. 1996). But, as for other commonly assessed species (including whiting, hake, red mullet and Atlantic horse mackerel), most efforts appear to reflect either unresolved or new selectivity issues and/or, in some cases, technological solutions that were not easily transferable among fisheries.

Irrespective of the mechanisms leading to repetitive research on relatively few species, this outcome provides a positive corollary for maximizing future progress in this field (which may not extend to 100% resolution but could nevertheless substantially ameliorate bycatch problems). That is, by developing and documenting the broad ranges of (1) experimental approaches and (2) potential modifications to reduce bycatch in fish trawls, we suggest studies of other species, in fisheries in the same or other parts of the world, might be progressed with less unnecessary repetition, and so ensure maximum cost–benefit in designing, refining and implementing solutions.

Considerations regarding experimental approaches

All the reviewed literature used at least one of three broad categories of experimental methods (covers, alternate hauls or paired comparisons)—albeit with considerable variability among technical details and the use of ancillary equipment (cameras or trawl-monitoring equipment)—to quantitatively assess the efficacy of modifications. Nevertheless, irrespective of the approach, there were some consistent confounding issues that, in many cases may have compromised identifying successful solutions to bycatch problems.

One of the key limiting factors has been failure to incorporate sufficient spatio-temporal replication in experiments. Many studies have shown that, in addition to sometimes even subtle technical factors within a trawl, a plethora of other biological, environmental and operational factors variably affect selectivity (Wileman et al. 1996; Broadhurst et al. 2016). These include, but are not limited to, water temperature and/or fish condition (Özbilgin et al. 2007); sea state (Somerton et al. 2018); diel patterns (Ryer et al. 2010); towing speed (Sala et al. 2007; Somerton and Weinburg 2001); haul-back delay (Madsen et al. 2008); catch weight (O'Neill et al. 2008); or water depth (Sala et al. 2008). The number and variety of such issues and fishery-specific importance mean that it is difficult to envisage their variability being captured in studies involving just two to five hauls over a few days in a fishing season (e.g. Sardá et al. 2006; Aydin et al. 2008; Özdemir et al. 2012, 2014; Rajeswari et al. 2013). In fact, several authors have acknowledged such factors probably contributed to differences in estimated parameter vectors for the same modifications tested in subsequent experiments (e.g. Brinkhof et al. 2020). Only by incorporating appropriate spatio-temporal replication across the full range of fishing conditions can such factors be adequately addressed. We acknowledge that operational costs usually restrict the days at sea available for experiments, but even within such constraints, experiments can still optimize replication given levels of variance using well-established cost–benefit procedures (Kennelly et al. 1993). And because of the number and variety of studies already done, the required parameters for such analyses should be readily available for many fisheries.

In addition to problems of replication, we suggest that many studies did not adequately assess for confounding effects of the experimental procedure on the treatments of interest. In particular, some designs of covers could affect the geometry and efficiency of trawls (Madsen and Holst 2002), and certainly fine-mesh liners in codends would displace more water forwards, potentially affecting the passage of fish (Broadhurst et al. 1999, 2002). Such effects were rarely tested for, or their confounding effects ignored. As one example, Madsen et al. (2001) recommended the kite cover for codends and subsequently demonstrated few confounding effects on selectivity (Madsen and Holst 2002), but despite this, most studies used hooped covers (but see Grimaldo et al. 2009). It should be a fairly simple procedure to confirm that codend/escape exit covers or liners do not affect the performances of either the trawl or the modifications using alternate hauls within the same experiments. And considering that repeated experiments have been done using consistent trawl designs in many fisheries, testing for ancillary cover effects might only need to be published periodically.

Many studies have also identified other technical factors that can confound trawl-gear comparisons, such as variable codend lengths or circumferences (Reeves et al. 1992; Sala and Lucchetti 2011), twine diameters (Lowry and Robertson 1996) and/or netting materials (Tokaç et al. 2004; O'Neill et al. 2016). But consistency among these factors was not identified (or stated) in many of the reviewed papers. Further, there was a tendency to present and discuss nominal mesh sizes (i.e. from the manufacturer) which were not stated as being measured (e.g. Özbilgin et al. 2005; Sola and Maynou 2018; Santos et al. 2016b), but if this did occur, mean mesh sizes were always different (e.g. Perez-Comas et al. 1998; Sala and Lucchetti 2011; Özbilgin et al. 2015). Because manufactures' nominal mesh sizes are not replicable, following Wileman et al. (1996) and Ferro and Xu (1996), we reiterate that these should be quantified and presented as mean sizes with variances. Similarly, all other technical specifications known to affect the selectivity of trawls should be stated.

Another issue regarding experimental procedures concerns the ease of their interpretation by fishing industries (who need to use any modifications) and managers (who need to legislate them). Many analyses involved producing selectivity ogives which present the probability of fish escaping at a particular size, and are needed to illustrate the absolute selectivities of gears independent of the population fished (Millar and Fryer 1999). Nevertheless, this approach is not particularly intuitive for fishers or managers, and contrasts with attempts to reduce bycatches in other fisheries where bycatches are usually discussed in terms of percentage reductions in whole weights or numbers (rather than sizes) (Pérez Roda et al. 2019; Kennelly 2020).

While we do not propose that the existing analytical methods be avoided, we suggest that there may be some scope for complementary approaches that, in addition to providing estimates of L_{50} and SR, also indicate total bycatch reductions due to the modification(s). Certainly, there appears to be a regional pattern in this regard, with European studies focusing more on experimental approaches using covers and therefore mostly reporting analyses of catches at size (e.g. Larsen and Isaksen 1993; Sistiaga et al. 2010; Ceylan and Sahin 2019). In contrast, studies in North America and Australia (although fewer in number) have been more biased towards alternate-haul experiments that concomitantly presented estimates of bycatch reductions as standardised predicted mean weights and/or numbers of animals (e.g. Lauth et al. 1998; King et al. 2004; Hannah et al. 2005; Graham et al. 2009; Eayrs et al. 2020). An additional advantage of combining approaches is that more data about the assemblages of species would be used, which may reduce the need for researchers to report results from the same cruises in separate papers (e.g. Özvarol 2016a, b; Larsen et al. 2016, 2018b; Pol et al. 2016a, b). Although presenting variations among broad categories of catches will not change the hypotheses tested, it might promote better understanding by industries which, in turn would encourage their greater development, refinement and ownership of solutions and, eventually, implementation of successful designs (Kennelly and Broadhurst 2002).

Some rationalization and consistency in experimental approaches would also benefit the future synthesis of data, especially those involving meta-analyses. The latter are increasingly being used to examine various parameters/estimates obtained in experiments to derive generalisable patterns over diverse situations (including those involving gear selectivity; Fryer et al. 2016; Melli et al. 2020) and subsets of the 203 papers summarized here could provide starting points for such work. However, as we identified in this review, inconsistency among papers in the estimation of parameters, variable scientific rigour (in terms of experimental designs and replication) and the non-reporting of null results, could compromise the validity of such analyses. That is, as is the case for individual experiments, confidence in any generalities that may come from meta-analyses of papers will be entirely dependent on the quality of the data used in them.

Choosing effective modifications

In examining the various categories of modifications developed to reduce bycatch in fish trawls, this review has assessed the utility, applicability, advantages and disadvantages of each. This led to the development of a framework which could be followed in future work, particularly for hitherto un-examined fisheries (Table 3). Often, key prerequisites to getting technological solutions into practice throughout a fishery are

Table 3 A framework for assessing modifications in demersal fish trawls

Consideration	Zone(s)	Modifications to test in sequence	Advantages	Disadvantages
First:	4	Choose the correct mesh size and shape for the smallest target species Choose the narrowest possible codend circumference and twine diameter To reduce catches of round fish, locate escape windows as close as possible to the catch and on the top of the codend To increase fish entering escape exits, consider guiding panels/stimulants (e.g. LEDs for nocturnal fishing or deep water) To reduce catches of small fish in fisheries with very few target species, consider size-selective grids To reduce catches of animals larger than the targeted species, consider species-selective grids	Simple changes usually improve selectivity This zone is usually common among fleets Changes can be flexible and easy-to-source Trawl monitoring equipment is not required	Modifications will not reduce drag or fuel usage Some modifications (e.g. square-mesh configurations) can alter through time Fish escape may occur after substantial interactions with the gear leading to some mortality
Next:	1–3	Choose the largest possible diamond-mesh sizes throughout zone 3 Choose the narrowest possible twine diameter Use a horizontal separator panel(s) to confirm species-specific behaviour in the trawl to inform the design of modifications Depending on species distributions inside the trawl, assess windows with different mesh shapes in the wings, or top panels To increase fish contact with panels/windows, consider guiding panels/stimulants (e.g. LEDs) Depending on species distributions inside the trawl, assess different types of ground gears Optimise bridle and sweep lengths for target species Optimise the spread ratio of the trawl	Simple changes usually improve selectivity Changes can reduce drag and fuel usage Changes can be flexible and easy-to-source Unwanted fish often escape the trawl entirely with low mortality	These zones are often not common throughout fleets It can be difficult to distinguish the key factors improving selectivity Trawl-monitoring equipment is usually required

that they not only reduce bycatches while maintaining target catches across most spatio-temporal scales, but are also simple and easy to understand and implement (Tucker et al. 1997). While we have no quantitative measure regarding the relative success and adoption of complex vs simple modifications, there was no clear trend towards either being more or less efficient, although simpler modifications were more common—especially in zone 4 of the trawl. Therefore, it seems appropriate for fledgling studies to first modify existing configurations within the codend to improve selection, simply because these are usually cheapest, within the (often-generational) experience of fishers, and codends are relatively homogenous within, and even between, fleets (Table 3).

More specifically, increasing lateral-mesh openings throughout codends via the use of larger T0 or similar sizes of T45 or perhaps T90 mesh (considering the operational issues with T45) to match the desired sizes and shapes of focus species would be a logical starting point, and especially for fusiform fish morphologically similar to the commonly assessed Atlantic horse mackerel, hake, haddock or red mullet (Halliday and Cooper 2000; Campos et al. 2003; Dereli and Aydin

2016). Alternatively, if there is industry resistance to alternative-mesh configurations, reducing codend circumference might be an even simpler option for T0 codends (Reeves et al. 1992; Galbraith et al. 1994; O'Neill et al. 2008; Graham et al. 2009), but with fewer benefits for T45 (Sala et al. 2016)—a similar result found for penaeid trawls (Broadhurst and Millar 2009). Narrower twine dimeters and/or avoiding double twine would similarly be appropriate options for all mesh configurations (Graham et al. 2009).

In some cases, instead of changes to the whole codend (that might affect strength or flexibility), installing relatively small windows in codends (mostly on the top or sides) made from meshes with larger lateral openings could have utility, although positioning is clearly important with locations closer to the catch most beneficial (e.g. Graham and Kynoch 2001; Graham et al. 2003) (Table 3). Such positioning was further discussed by Herrmann et al. (2015a, b) and reaffirms earlier research in penaeid trawls where displaced water was shown to assist fish to escape via proximal openings (Broadhurst et al. 1999, 2002). A consequence of these effects is that they imply confounding impacts of the use of codend liners and/or inappropriate cover designs (discussed above).

Grids are also clearly successful zone-4 options, although their choice needs to be very fishery-specific (Table 3). That is, size-selective grids, and especially the flex-grid and variants might warrant future extension and assessment in those fisheries with few species or where most bycatches are juveniles of the targets (e.g. Larsen and Isaksen 1993; Sardá et al. 2004; Eigaard et al. 2012; Herrmann et al. 2013b; Larsen et al. 2016, 2018b; O'Neill et al. 2008; Sistiaga et al. 2018). In addition, using guiding panels and deflectors to direct fish toward such grids can augment selectivity (e.g. Halliday and Cooper 1999; Kvamme and Isaksen 2004; Kvalsvik et al. 2006; Grimaldo et al. 2015). But in some cases, compared to size-selective grids, simpler modifications like increasing codend mesh size could be just as effective (Jørgensen et al. 2006; Grimaldo et al. 2008). In contrast, and as for penaeid trawls, there appear to be few simple options for excluding charismatic megafauna like turtles, seals and elasmobranchs other than species-selective grids, although subtle refinements (e.g. to bar shape, size and design) can be made to maintain target catches of fish (Wakefield et al. 2017; Vasapollo et al. 2019).

Concomitant with simple zone-4 modifications as a starting point for improving trawl selection are several promising options for the anterior sections of the trawl (Table 3). However, considering there are few examples in the literature where the relative utility of individual multiple-zone configurations could be deciphered, all anterior modifications need to be assessed in isolation and with carefully considered experimental controls. Simple options involve entire areas or windows with larger lateral-mesh openings (like those used in zone 4) and designed to partition species based on size (e.g. Milliken and DeAlteris 2004; Bayse et al. 2016; Santos et al. 2016b; Bonanomi et al. 2020). But most modifications in these trawl sections rely on species-specific behavioural responses. As a broad distinction, many roundfish rise up (but not all; e.g. cod), while flatfish remain low; a characteristic which can and has been used to separate species using modifications like horizontal panels (Engås et al. 1998; Ferro et al. 2007; He et al. 2008; Holst et al. 2009; Park et al. 2012) or topless trawls (e.g. Chosid et al. 2008; Krag et al. 2015; Eayrs et al. 2017).

Certainly, horizontal panels might be positioned in studies of unassessed trawls to provide initial information on the preferred orientations of the key species as a precursor to making simple changes to promote bycatch escape (He et al. 2008). Light emitting diodes might then also be tested to exploit any identified behavioural differences (Lomeli et al. 2018). For example, Southworth et al. (2020) used a T45 window with and without LEDs in the top body of a scallop trawl and showed that the non-illuminated window reduced catches of whiting and haddock in shallow water while illuminating the panel in deep water reduced haddock and flatfish catches.

Notwithstanding the potential complementary benefits on overall trawl selection associated with modifying the anterior sections, the reviewed studies indicated that considerable ancillary information concerning the behavioural subtleties of focus species in nets is needed, and incorporating often wide spatio-temporal variability in key environmental parameters (Wardle 1989). In addition to sufficient replication, this often requires quite specialized equipment including cameras and/or sonar (e.g. Krag et al. 2015; Cotter et al. 1997; Engås et al. 1998; Ferro et al. 2007). Furthermore, changes in the anterior section affect whole trawl geometries (i.e. spread ratios and headline height) which means trawl-monitoring equipment needs to be used and any effects incorporated into analyses (e.g. Lauth et al. 1998; Fiorentini et al. 1999; Milliken and DeAlteris 2004; Krag et al. 2015). Such implicit requirements of zone 1 to 3 modifications and their isolated testing may limit attempts at resolving bycatch issues in this part of the trawl in some fisheries, especially those in developing countries.

Nevertheless, advantages of modifying the anterior trawl include minimizing escape mortalities because, unlike the close confines of zone 4, fish are less likely to contact netting or other animals and so get injured or killed (Table 3). Further, because this area dictates most of the system drag, there is considerable potential to reduce operating costs through so-called 'low impact fuel efficient' designs (LIFE; Suuronen et al. 2012) which can, in turn, facilitate adoption throughout fleets due to concomitant fuel savings (McHugh et al. 2017).

Conclusions

This review demonstrated that most efforts towards reducing bycatch in fish trawls have involved relatively few species in the North Atlantic Ocean which, when combined with considerable collaboration among researchers, has precipitated significant similarity in the designs of modifications and ways to assess them. But despite a geographic bias in effort, within this region are diverse fisheries that range from nearly mono- to multi-specific targeting various fish sizes and shapes (round and flatfish) and with divergent behaviours. This means the reviewed studies encompass sufficient variety to provide excellent starting points for unassessed fisheries, especially with respect to simple modifications like T45/90 mesh throughout codends, or as posterior top-orientated windows.

The less-studied, non-European fisheries also offer unique perspectives, including variability in operations that could benefit existing modifications, and experimental approaches based more towards alternate haul and paired-gear comparisons that facilitate relative comparisons of absolute catches—which can be more easily understood by stakeholders. But no matter the region or basic approach, a major conclusion from this review is that maintaining a rigorous empirical framework to adequately test and quantify the efficacy of individual modifications, while conveying implications about catches and bycatches to stakeholders, is as important as the simplicity and reliability of the modifications themselves.

While we advocate zone-4 modifications as an excellent starting point for unassessed fisheries, wherever possible these should be complemented by a more holistic LIFE approach to resolving issues in trawl fisheries (Suuronen et al. 2012). Fishers are more likely to refine and adopt modifications that reduce bycatch if there are additional benefits such as minimising fuel usage via reductions in drag through simple modifications in zones 1 to 3. And of course, engaging industries in all such work should dramatically increase the eventual implementation of successful solutions.

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No effects of ground-gear diameter on the performance of a south-eastern Australian fish trawl

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ABSTRACT

As part of attempts at improving the selectivity of south-eastern Australian fish trawls, the effects of ground-gear disc diameter on trawl engineering and catching performances were investigated. Three conventional disc diameters (100 mm or 4 in., 178 mm or 7 in. and 254 mm or 10 in.) at the centre third of the ground gear were alternated during 12 days of conventional fishing. There were no significant effects of ground-gear configuration on otter-board spread or the headline height of the trawl. Rather, significant influences were limited to depth affecting positive and negative relationships with otter-board spread and headline height, and speed over the ground evoking a positive effect on otter-board spread. Catches of four retained species (bigeye ocean perch, *Helicolenus barathri*, pink ling, *Genypterus blacodes*, ocean leather jacket, *Nelusetta ayraud*, and tiger flathead, *Platycephalus richardsoni*) and two discards (smooth whiptail, *Malacocephalus laevis* and falseband whiptail, *Coelorinchus maurofasciatus*) and the sizes of three of these species, were not significantly different among ground gears. The results imply minimal benefit in varying conventional ground-gear configurations for reducing unwanted catches.

1. Introduction

Benthic trawling for fish occurs globally and is important to the economics of most coastal countries, but also is characterised by often poor selectivity, accounting for 25 % of the world's discarded catches (Pérez Roda et al., 2019). Historical recognition of the selectivity issues associated with fish trawling has manifested in decadal efforts at modifying trawls, and mostly via alternative mesh shapes and/or sizes in the posterior sections or 'codends/extensions' (Kennelly and Broadhurst, 2021). In many cases, significant and consistent improvements have been realised, although selectivity issues remain unresolved in most fisheries (Kennelly and Broadhurst, 2021).

Beyond modifying codends/extensions, in some fisheries, selectivity improvements have also been achieved via changes to anterior-trawl sections; albeit with often considerable variability among performances (Kennelly and Broadhurst, 2021). In particular, some studies have assessed changes to ground-gear configurations, with the key mechanism involving raising the footrope (i.e. the bottom section of the trawl; Brewer et al., 1996; Krag et al., 2010) and/or removing some of its surface area (Fakioğlu et al., 2022); which can simply encompass existing designs (e.g. Engås and Godø, 1989; Lauth et al., 1998) or new, alternative ground gears (e.g. Brinkhof et al., 2017; Larsen et al., 2018). In some fisheries, these changes have reduced the catches of small fish (which escaped between the ground gear and higher footrope); but effects are not always apparent, reflecting variability in species-specific behaviours (Dahm, 2000; Piasente et al., 2004). Such differences preclude interpolating simple ground-gear changes across fisheries without additional assessment (Lauth et al., 1998; Dahm, 2000; Krag et al., 2010).

One fish-trawl fishery for which there have been ongoing efforts at improving codend selectivity (Broadhurst and Kennelly, 1995; Knuckey and Ashby, 2009; Graham et al., 2009; Hunt et al., 2014; Broadhurst et al., 2022; Broadhurst and Millar, 2022), but fewer efforts at modifying anterior-trawl sections (Broadhurst and Kennelly, 1995) and no work

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with ground gears, is off southern Australia. This fishery extends along the continental shelf from Sydney, New South Wales (NSW; 33.58° S, 151.33° E), south around Tasmania and west to Cape Leeuwin, Western Australia (34.37° S, 115.13° E) and currently comprises ~ 37 active single-rigged trawlers. Most vessels fish off the south-eastern coast as part of the 'Commonwealth trawl sector' (CTS) where they all use similar otter trawls with ~ 30–45 headline lengths to target ~ 20 species; among which tiger flathead, *Platycephalus richardsoni* is dominant (Broadhurst et al., 2023; Novaglio et al., 2018). The CTS typically harvests ~ 12,000 t per annum valued at > $AU 40 million, but fishers also discard non-commercial catches which can include small individuals of targeted species and > 280 other unwanted species that cumulatively account for 40–60 % of the total catches (Knucky and Ashby, 2009).

Fishing mortality by CTS trawlers is mostly managed via output controls (e.g. quotas), but also with input controls such as minimum mesh sizes that were mandated following selectivity studies (e.g. Broadhurst and Kennelly, 1995; Knuckey and Ashby, 2009). Specifically, a minimum of 115 mm stretched mesh opening (SMO) is permitted in the trawl wings and body, and 90 mm SMO in the codend. If the codend meshes are constructed of double twine, fishers must use larger mesh (102 mm SMO) or install a bycatch reduction device in the top forward section comprising a ~0.6 m^2 panel of meshes made from 90 mm SMO and hung on the bar so they are either square-shaped or as T90 (Knuckey and Ashby, 2009; Broadhurst et al., 2022).

Most CTS trawlers use ground gear with threaded rubber discs that typically are 65–300 mm in diameter (Ø) to allow trawls to be deployed across uneven substrate (Fig. 1). Like in many overseas fisheries (Dahm, 2000), CTS fishers construct their ground gears with the centre third made from larger discs than the adjacent thirds either side. While there are no restrictions on ground-gear disc sizes for vessels working offshore, those working close to shore (< 3 nm or 5.6 km) off NSW are restricted to a maximum Ø of 100 mm based on the perception that larger discs will facilitate access to inshore high-relief reefs. However, there are no scientific data to support the current ground-gear legislation. Anecdotal reports from fishers indicate that like for some overseas fisheries, lowering the footrope closer to the seabed via smaller discs can increase the catches of unwanted small fish at some times and locations.

While negative relationships between footrope height and catches of some species have been reported elsewhere (e.g. Krag et al., 2010), there are no data describing the effects on catches associated with ground-gear disc size in the CTS, which is a prerequisite to standardising regulations across depths in the fishery. Considering the above, the aim here was to test the hypothesis of no differences in the engineering or catching performances of a conventional CTS fish trawl rigged with three maximum disc Ø (100, 178 and 254 mm or 4, 7 and 10 in) encompassing most configurations used throughout the fishery.

2. Methods

The experiment was done off Ulladulla, NSW (37.35° S; 150.46°E) between 27 April and 23 May, 2021 using a trawler rigged with a conventional, singled-rigged 'H-top' trawl (Hampidjan™) (Table 1, Fig. 1a). The trawl was attached to 20-m bridles and 220-m sweeps (20-mm Ø combination rope) and spread by steel V-doors (Table 1). The vessel was equipped with a Scanmar trawl-monitoring system to measure the otter-board spread and headline height of the trawl and a Lowrance global positioning system (GPS) to record the distance travelled and speed over the ground (SOG).

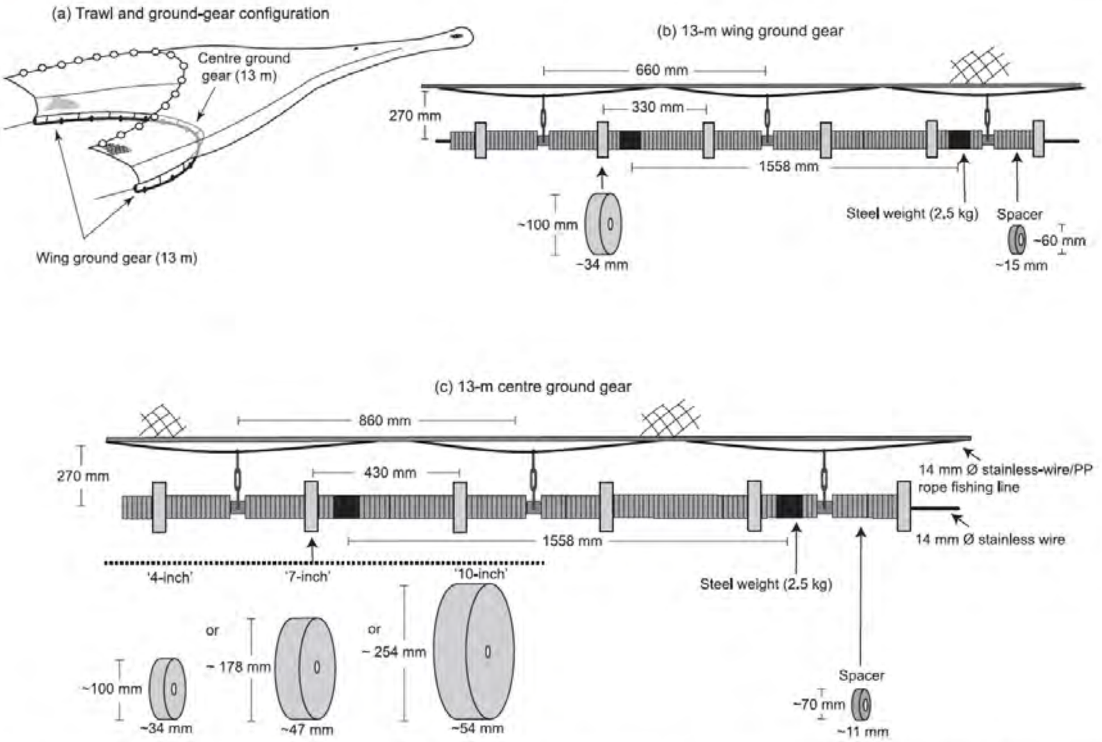

Fig. 1. Schematic diagram of (a) trawl and ground-gear configuration with (b) 13-m wing sections, and (c) centre section (showing the three assessed treatments: 4-; 7- and 10-inch discs). Ø, diameter; PP, polypropylene.

Table 1
General technical specifications for the 'H-Top' trawl used in the experiment. N, normals; B, bars.

Variable	Dimensions
Steel V-otter boards	750 kg and 2.7 m^2 each
Sweep length	220 m
Bridle length	20 m
Headline length	38.3 m
Ground gear	39.0 m
Ground-gear off-bottom extension	7.0 m
Number of seams	2
Side taper	2N3B
Stretched mesh openings (mm)	
Top panel of wings	152
Bottom panel of wings	115 and 152
Top panel of body	152
Bottom panel of body	115
Extension and codend	90

2.1. Ground-gear configurations

The trawl ground gear (39 m) was separated into thirds; two 'wings' either side of a centre section and each 13 m long (Fig. 1). Each wing section comprised 60-mm Ø discs termed 'spacers' separated by 2.5-kg steel weights every 1.56 m, and 100-mm Ø discs every 0.30 m; all threaded onto 14-mm Ø stainless steel wire ('ground-gear line') for total weights of 89 kg each (Fig. 1b). These wing sections were permanently shackled to the footrope (14-mm Ø stainless-steel wire) via 270-mm stainless-steel 'toggles' (Fig. 1b).

Three centre sections were constructed so they could be alternately shackled at the same marked locations to the footrope and also adjacent to the wing sections. The three centre sections all similarly comprised 70-mm Ø spacers separated by 2.5-kg steel weights threaded onto 14-mm Ø stainless steel wire as above and with 270-mm toggles, but had different maximum disc (n = 29 section^{-1}) Ø of either: (1) 100 mm (termed '4-inch'; for a total weight of 105.60 kg); (2) 178 mm ('7-inch'; 130 kg); or, (3) 254 mm ('10-inch'; 142 kg); each spaced 480-mm apart (Fig. 1c). Average disc widths were 34, 47 and 54 mm, respectively providing bottom contacts of ~ 986, 1363 and 1566 mm, respectively (Fig. 1).

The three centre sections were alternately fished on the trawl in a blocked design comprising 36 deployments during 12 fishing days with three deployments (~150 min) each day between 04:00 and 15:30 and two ground gears tested on each fishing day, providing two replicates of each configuration every two days (Supplementary Table 1). Prior to deployment, the tested centre section was secured to the footrope at the marked locations. The trawl was then deployed across conventional fishing grounds randomly selected from available options according to weather and environmental conditions, and encompassing similar depth ranges across replicate treatments.

2.2. Data collected

The technical and environmental data collected during each deployment included the: (1) trawled location, distance (m) and duration (warp winch brakes on and off); (2) SOG (m s^{-1}); (3) otter-board spread (m); (4) headline height (m); and (5) fishing depth (m). The latter four variables were logged every 15 min to provide an average for each deployment.

At the end of each deployment, the codend was retrieved, emptied into a designated holding area with a measured volume, and the total catch weight estimated. Commercially important species were separated and graded by the crew into 55-l boxes, and all were weighed, counted and retained. The total weight of discarded catch was derived by subtracting the retained catch from the total catch, and a subsample of several boxes was separated. Any discarded commercial species and the most abundant non-commercial discards were then individually counted and weighed in the subsamples and extrapolated to the total. The total number of species was also counted. All key species (e.g. those retained and the most abundant discards) in the subsampled catches were measured to the nearest 1 cm total length (TL).

2.3. Data analyses

Data for otter-board spreads, headline heights and standardized (for swept area and log-transformed to act multiplicatively) catches (numbers and weights) were analysed using linear mixed models (LMM) with 'ground-gear configuration' considered fixed while 'days' were random factors. To explain variability among ground-gear configuration for otter-board spread and headline height, the fished SOG and depth were also included as co-variates. A quadratic term in depth was included to explain variability in catches due to depth preference. The significance of ground-gear configuration was determined using the change in deviance from a LMM obtained by excluding the ground-gear configuration term (Millar, 2011).

Differences in the size frequencies of key species between each pair of ground gears (4- vs 7-inch, 7- vs 10-inch, and 4- vs 10-inch) were explored using relative selectivity analysis (Broadhurst et al., 2018) which is also commonly known as "catch comparison analysis" (Herrmann et al., 2017). This approach follows the 'SELECT' (Share Each LEngths Catch Total; Suuronen et al., 1991; Millar, 1992; Wileman et al., 1996; Millar and Fryer, 1999) approach which proceeds by modelling the proportions at length of the total catch (summed over both ground gears) that is caught by one of the two ground gears. For example, in the case of 4- vs 10-inch ground gears and for length-class l, the proportion of the total catch that is caught in the 10-inch gear is denoted

$$y_l = \frac{n_l^{10}}{n_l^4 + n_l^{10}}$$

where n_l^4 and n_l^{10} are the numbers caught in the 4-inch and 10-inch ground gears, respectively.

The proportions y_l were assumed to be binomially distributed. Catch proportion curves $c(l)$ were fitted by maximizing the binomial log-likelihood function.

$\sum_l n_l(y_l \log(c(l)) + (1-y_l)\log(1-c(l)))$ where $n_l = n_l^4 + n_l^{10}$. Note that the catch curve $c(l) = 0.5$ corresponds to identical catchability of all lengths in both gears. Several forms of $c(l)$ were considered, including cubic regression splines on the logit scale

$$c(l) = \frac{\exp(cs(l))}{1 + \exp(cs(l))}$$

where $cs(l)$ denotes the cubic regression spline. Assuming that smaller fish more easily escape under the footrope it would be valid to fit a monotone increasing catch proportion curve that increases to an upper asymptote for large sizes that will not escape under either footrope. Such a curve is

$$c(l) = \frac{r(l)}{k + r(l)}$$

where $0 < k$ and $r(l)$ is a monotone increasing curve such as the logistic or Richards. This formulation also permits monotone decreasing catch proportions should $r(l)$ be monotone decreasing with length. These catch proportion curves can be fitted using established software for paired hauling (Wileman et al., 1996). The fits were implemented in the R environment using the SELECT package (Millar, 2021; R Core Team, 2021). The SELECT package also facilitated bootstrapping (Millar, 1993) to allow for the effect of between-haul variability (Millar et al., 2004) which would otherwise invalidate the model due to failure of the binomial assumption.

A permutation test was deployed for checking the statistical significance of any difference in size frequencies between pairs of ground-gear configurations. Using the above relative selectivity analyses, the permutation test compared the actual likelihood ratio test statistic (LRT) for the null hypothesis $c(l) = 0.5$ to the distribution of the LRT after permutating ground gears; that is after randomly relabelling the ground-gear treatments amongst the deployments. The randomization test p-value is given by the proportion of the LRTs from fits to the randomized ground gears that exceed the actual LRT. The bootstraps and randomizations each used 1000 resamples.

3. Results

In total, we caught 12.8 and 9.8 t of retained and discarded catches, respectively during the 36 deployments (145–165 min), which were completed across depths from 111 to 577 m and at similar SOGs (1.2–1.8 m s^{-1}; total mean ± SE of 1.5 ± 0.02 m s^{-1}) (Supplementary Tables 1 and 2). The retained catches comprised 30 species, but 74 % by weight was dominated by bigeye ocean perch, *Helicolenus barathri* and pink ling, *Genypterus blacodes* in water > 400 m, and ocean leather jacket, *Nelusetta ayraud*, and tiger flathead, *Platycephalus richardsoni* at shallower depths (< 210 m; Supplementary Tables 1 and 2). Discarded catches comprised > 16 species, including some individuals of targets other than the four above, but the most abundant were smooth whiptails, *Malacocephalus laevis* and falseband whiptails, *Coelorinchus maurofasciatus*, respectively (15 % of the total weight of discards) and caught in water > 400 m (Supplementary Tables 1 and 2). These six species were caught in sufficient quantities among replate deployments to form the basis of analyses below.

3.1. Engineering data

The LMMs applied to the data for the otter-board spread and headline height of the trawl revealed no significant effects of ground-gear configuration, with very similar predicted means (± SE) when rigged with the 4-inch (152.0 ± 2.6 and 3.9 ± 0.1 m), 7-inch (152.1 ± 2.65 and 3.6 ± 0.1 m) and 10-inch (153.9 ± 2.6 and 3.9 ± 0.1 m) configurations ($p > 0.05$). However, regardless of ground-gear configuration, the fishing depth and SOG both significantly and positively affected otter-board spread and therefore the trawl opening, while depth also significantly and negatively affected headline height (LMM, $p < 0.001$). These differences manifested as a 13-m increase in otter-board spread and a 33 cm reduction in headline height for every additional 100 m of depth, and a 3.6 m increase in otter-board spread for every 0.1 m s^{-1} increase in SOG.

3.2. Catches and sizes

There were no significant effects of ground-gear configuration on any of the standardized (ha^{-1} trawled) catches (LMMS, $p > 0.05$; Table 2, Fig. 2). Certainly, there were minimal differences in predicted means across ground-gear configurations among the retained catches, although for the retained bigeye ocean perch and discarded falseband and smooth whiptails, mean catches were slightly lower in the trawl when rigged with the 7- and 10-inch than with the 4-inch ground gear—albeit with considerable variability (Fig. 2d, g and h).

Sufficient size-frequency data were available to fit catch proportion curves for falseband and smooth whiptails and tiger flathead (Fig. 3 and Supplementary Figs. 1 and 2). In all cases the spline fits produced highly irregular shaped curves and proved to be numerically unstable in some of the bootstrap and randomization runs. The monotone form with logistic shaped $r(l)$ was the preferred fit based on the Akaike information criterion (AIC). No permutation p-values were statistically significant at the 5 % level for any of the three pairwise ground-gear comparisons of the three species (Fig. 3 and Supplementary Figs. 1 and 2). For this reason, relative selectivity results only for the comparison between the smallest (4-inch) and largest (10-inch) ground gears are presented in Fig. 3, in order to assess if there were any common trends amongst the three species (Fig. 3). For the whiptails, the non-significance can be attributed to relatively large catches of small fish in one or two of the tows with the 10-inch ground-gear configuration (Fig. 3a and b). For tiger flathead, the observed proportions show a unimodal pattern, again due to variability in just one or two tows (Fig. 3c). The dearth of small flathead also limited the strength of any clear pattern (i.e. relatively fewer fish < ~ 30 cm TL in the trawl with the 10-inch ground-gear configuration; Fig. 3c).

Table 2
Summaries of the total numbers, weights (kg) and key size ranges (where applicable) of catch variables and their p-values from linear mixed models investigating variability (as ha^{-1} trawled) due to ground-gear configuration (4-, 7- and 10-inch centre pieces). Fishing days were included as a random blocking effect. Na, not applicable. TL, total length.

Variable	Quantity caught (kg)	Size range (cm TL)	p
Retained catches			
Total wt	12,798	Na	0.82
Total species no.	Na	Na	0.96
Ocean leatherjacket, *Nelusetta ayraud* no.	5382	24–52	0.33
Ocean leather jacket wt	2900	Na	0.39
Bigeye ocean perch, *Helicolenus barathri* no.	6354	20–44	0.18
Bigeye ocean perch wt	2876	Na	0.15
Pink ling, *Genypterus blacodes* no.	1125	47–106	0.66
Pink ling wt	1941	Na	0.46
Tiger flathead, *Platycephalus richardsoni* no.	2333	24–56	0.91
Tiger flathead wt	1171	Na	0.89
Discarded catches			
Total wt	9804	Na	0.99
Total species no.	Na	Na	0.49
Smooth whiptail, *Malacocephalus laevis* no.	7715	16–44	0.12
Smooth whiptail wt	531	Na	0.41
Falseband whiptail, *Coelorinchus maurofasciatus* no.	6061	15–39	0.24
Falseband whiptail wt	406	Na	0.35

4. Discussion

The data here contribute toward the few empirical studies assessing the effects of varying ground gear on fish trawls for affecting geometry and selectivity (Engås and Godø, 1989; Brewer et al., 1996; Lauth et al., 1998; Krag et al., 2010; Brinkhof et al., 2017; Larsen et al., 2018). However, while some of the previous work has shown considerable species-specific variability in performances among ground-gear designs (e.g. Brewer et al., 1996) none, including those assessing similar ground-gear changes as those here (e.g. Dahm, 2000), have accepted the null hypothesis across all assessed species. The negligible effects observed here can be discussed by first considering the detected and probable effects of the measured changes on trawl geometry, and then the possible behaviours of the key species.

Compared to the configuration comprising the 4-inch ground gear, those with the 7- and 10-inch ground gears slightly increased seabed contact (~986(~ 986 vs 1363 and 1566 mm) and therefore surface areas (by similar amounts), weights (~ 106 vs 130 and 142 kg), and the heights of both the ground-gear line and footrope off the seabed (by 40 and 77 cm, respectively). However, all of these changes were negligible to the remaining system drag created by the twine area and spreading mechanisms (McHugh et al., 2017; Kennelly and Broadhurst, 2021). Certainly, there were no significant effects of ground-gear configuration on otter-board spread or headline height. Rather, as for previous studies, changes among the latter were explained by depth and/or SOG and established mechanisms (e.g. Weinberg et al., 2002; Weinberg and Kotwicki, 2008). Specifically, as depth increases, and the ratio of warp-deployed-to-depth decreases, the divergence angle of the warp

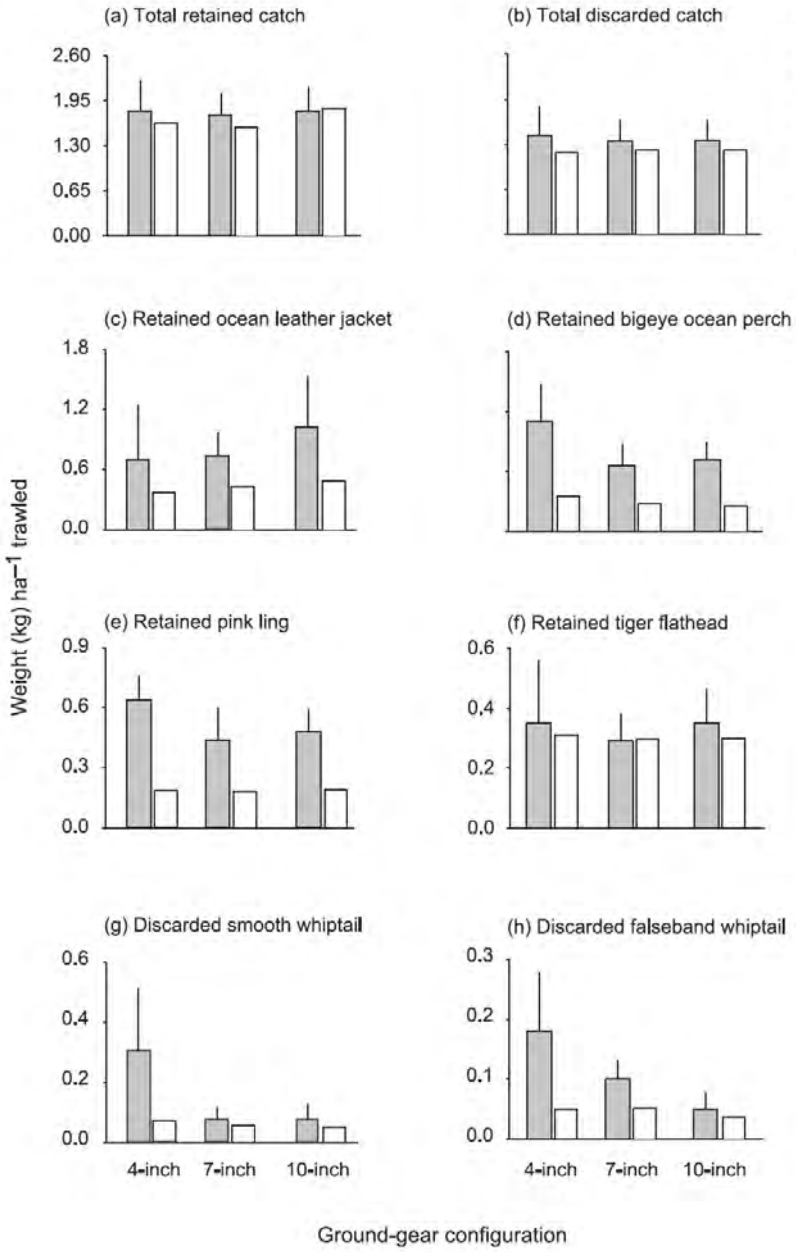

Fig. 2. Differences in raw (± SE; grey histograms) and predicted (white) mean weights ha^{-1} trawled (derived using otter-board spread) between the trawl when rigged with the 4-, 7- and 10-inch ground gears for the total (a) retained and (b) discarded catches, retained (c) ocean leatherjacket, *Nelusetta ayraud*, (d) bigeye ocean perch, *Helicolenus barathri*, (e) pink ling, *Genypterus blacodes*, and (f) tiger flathead, *Platycephalus richardsoni* and discarded (g) smooth whiptail, *Malacocephalus laevis* and (h) falseband whiptail, *Coelorinchus maurofasciatus*.

reduces and this allows trawl spread to increase, and with a concomitant reduction in headline height (Weinberg and Kotwicki, 2008). Also, at slower SOGs, there would be less drag created by the gear, allowing it to be spread wider by the otter boards because they would have greater seabed contact pressure and therefore more ground shear (Weinberg et al., 2002).

While depth-affected increases or decreases in trawl spread and any subsequent changes to headline height would also conversely affect contact pressure of the ground gear on the seabed, this did not manifest as any significant changes among the three ground gears to the catches or sizes of shallow-water (ocean leatherjacket and tiger flathead) or deep-water (remaining four) species. Previous studies have shown similar changes to ground gears involving variations in footrope height/distance to ground-gear line significantly affected catches of individual species (e.g. cod, *Gadus morhua*; Engås and Godø, 1989; Brinkhof et al., 2017 and haddock, *Melanogrammus aeglefinus*; Larsen et al., 2018), while other studies have noted more variable impacts (e.g. for haddock; Dahm, 2000). As one example, Dahm (2000) similarly compared three

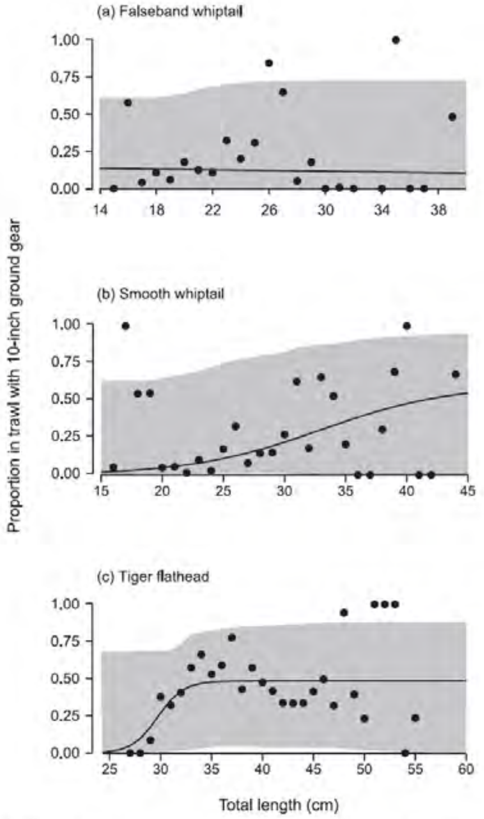

Fig. 3. Plots of catch proportion curves showing the proportion of the combined catch from the 4- and 10-inch ground gears that was caught in the 10-inch ground gear. (a) falseband whiptail, *Coelorinchus maurofasciatus*, (b) smooth whiptail, *Malacocephalus laevis*, and (c) tiger flathead, *Platycephalus richardsoni*. The grey shading shows 95 % confidence intervals for the catch proportion at each length.

ground-gear centre sections broadly comprising maximum disc Øs of 89, 200 and 305 mm and showed (via small-meshed collection bags under the ground gear) that small individuals of some species (grey gurnard, *Eutrigla gurnardus*, whiting, *Merlangius merlangus* and horse mackerel, *Trachurus mediterraneus*), but not others (haddock and herring, *Clupea harengus*) were able to escape under the ground-gear line as disc size increased. These results were attributed to variable species-specific escape behaviours.

Other studies have also shown species-specific differences, although the changes to the height of the footrope were much greater than assessed here (e.g. Brewer et al., 1996). There have been few published accounts of the observed behaviour of the key species here in response to various trawls, but using cameras, Piasente et al. (2004) described the reactions all species/groups except ocean leather jacket. Most species displayed fairly limited responses at the anterior trawl, with mostly haphazard bursts of swimming up off the bottom. The only species noted to escape under the footrope and between the ground-gear discs was tiger flathead (a mostly dorsally compressed, benthic species). Using cameras, Yanase et al. (2009) similarly observed 15 % of this species and the congeneric, eastern sand flathead, *Platycephalus bassensis* passing under the ground gear of a much smaller trawl. Presumably, the variation in height of discs in the present study (up to 77 mm) was insufficient to manifest as any greater increase in the escape behaviour of these fish, and possibly because all sizes could fit under the ground-gear line of the 4-inch ground gear. The fitted catch proportion curve for tiger flathead might imply some effect for small fish (< ~ 30 cm TL), but there were very few individuals at these sizes, possibly supporting the observed negligible effect.

The data here support no effects of disc sizes within the most common size ranges (i.e. used by ~ 87 % of the fleet) on the engineering or catching efficiencies of a generic regional trawl across the studied area. While this area and the species encountered were typical of the broader fishery, it is important to acknowledge that there might be spatial variation in performances. Also, some vessels working in deep water use 305 mm (12-in.) discs, although this would only increase the height of the ground-gear line (compared to the 10-inch ground gear here) by ~ 26 mm. Any future research with ground gears might warrant investigating a greater range of treatments across the broader fishery, including various depths.

Nevertheless, like for penaeid-trawl fisheries (McHugh et al., 2017), the outcomes from this preliminary work support future improvements due to the selectivity of south-eastern Australian fish trawls concentrating on the anterior body and codend, rather than the ground gear. Such work should be given priority considering the relative amounts of discards observed here, which ranged between ~ 36 % and 41 % of the predicted mean total catch deployment^{-1} among ground-gear configurations and appear quite consistent, considering other recent studies in the fishery (e.g. Broadhurst and Millar, 2022; Broadhurst et al., 2023). Simple solutions that mitigate discarding are clearly a priority. But, as part of any future work, understanding species behaviour is imperative. There are few data for the key species, and many of these are quite different to those in more studied European and North American fisheries (mostly cod and haddock) which precludes interpolation (Kennelly and Broadhurst, 2021).

CRediT authorship contribution statement

Conceptualization (MKB, IAK and RBM); Data curation (MKB); Formal analysis (RBM); Funding acquisition (MKB); Investigation (MKB and IAK); Methodology (MKB, IAK and RBM); Project administration (MKB); Resources (MKB); Software (MKB and RBM); Supervision (MKB and IAK); Validation (MKB); Visualization (MKB, IAK and RBM); Writing – original draft (MKB); Writing – review & editing (MKB, IAK and RBM).

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data Availability

Data will be made available on request.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.fishres.2023.106695.

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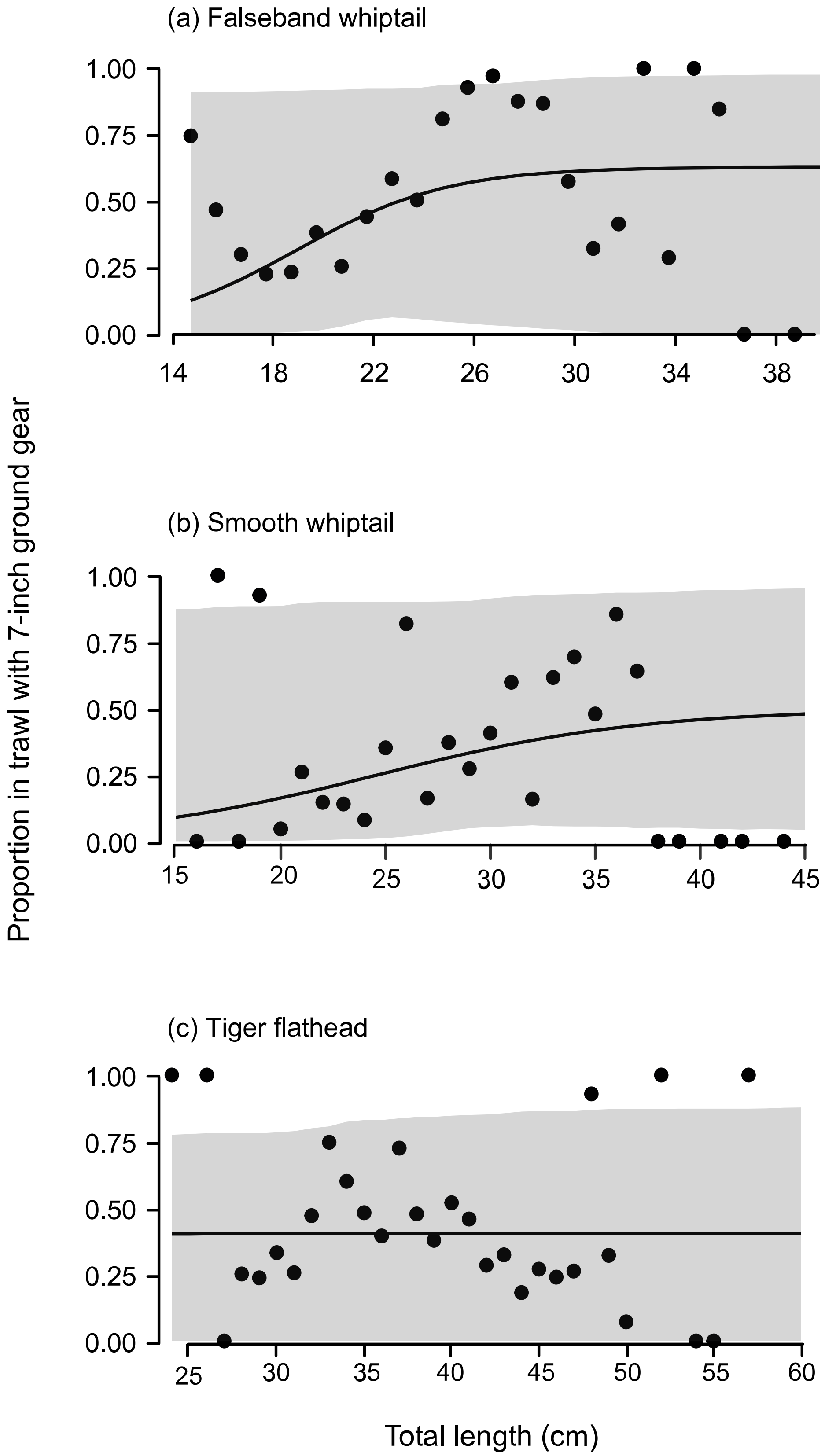
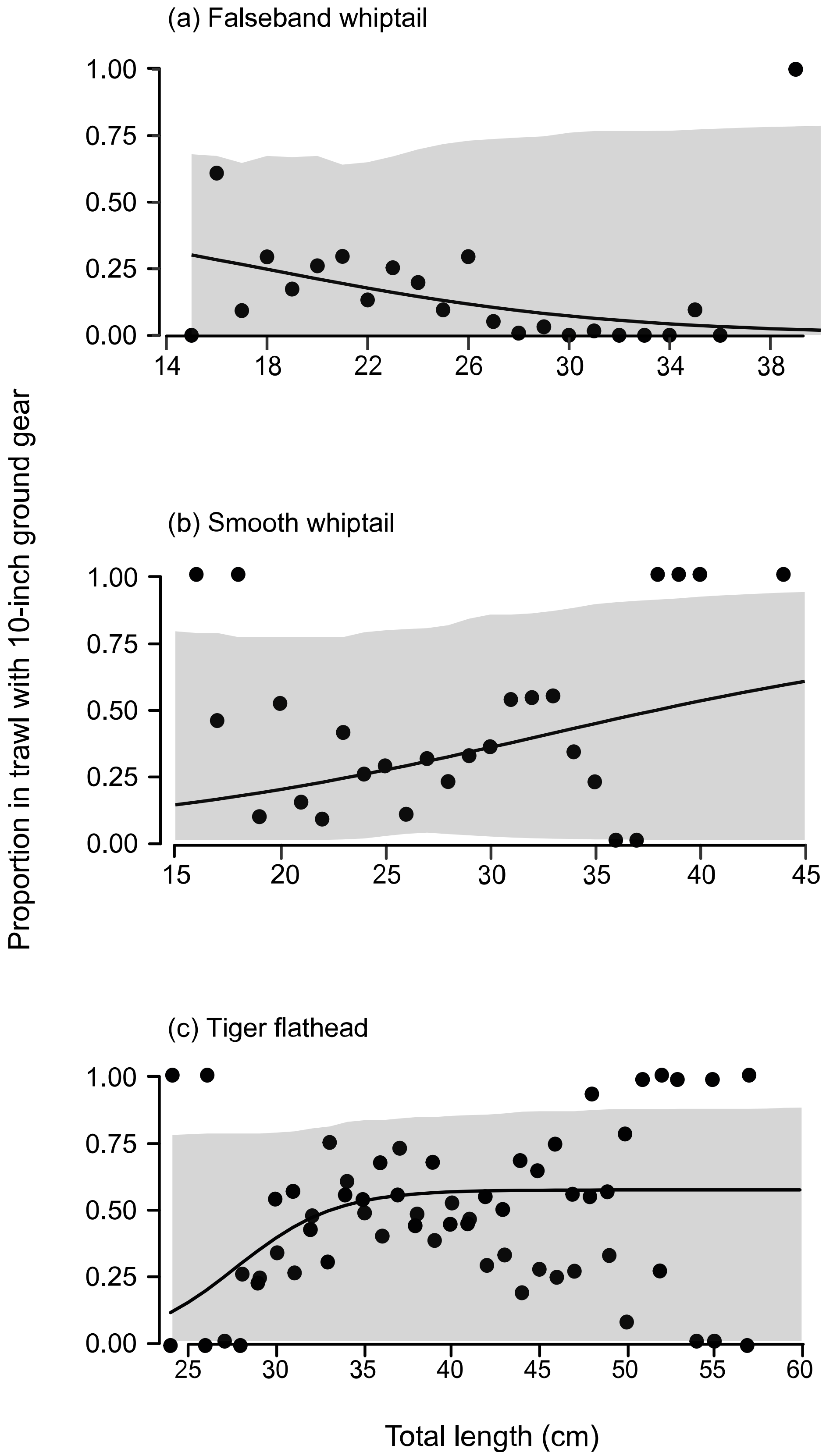
Supplementary material

Supplementary Table. List of species (common and Latin names) caught in descending total weights and their numbers and % weights discarded during 36 deployments of a generic fish trawl rigged with three different ground gears off Ulladulla, New South Wales, Australia during April and May, 2021. Na, not available.

Common name	Latin name	Wt (kg)	No.	% discarded (wt)
Bigeye ocean perch	*Helicolenus barathri*	2927.4	6844	1.8
Ocean leatherjacket	*Nelusetta ayraud*	2900.4	5382	0.0
Pink ling	*Genypterus blacodes*	1940.6	1125	0.0
Australian longnose skate	*Dentiraja confusus*	1723.3	460	100.0
Tiger flathead	*Platycephalus richardsoni*	1177.6	2377	0.6
Australian angelshark	*Squatina australis*	1130.8	Na	17.9
Miscellaneous stingarees	*Urolophus* spp.	1048.4	Na	100.0
Redfish	*Centroberyx affinis*	823.9	Na	10.1
Deepsea flathead	*Hoplichthys haswelli*	559.6	1611	100.0
Red gurnard	*Chelidonichthys kumu*	549.5	Na	62.5
Smooth whiptail	*Malacocephalus laevis*	530.5	7715	100.0
Yellowtail scad	*Trachurus novaezelandiae*	439.2	6253	100.0
Falseband whiptail	*Coelorinchus maurofasciatus*	406.4	6061	100.0
Grey morwong	*Nemadactylus douglasii*	381.6	1359	67.5
Blue mackerel	*Scomber australasicus*	265.5	Na	100.0
Southern sawshark	*Pristiophorus nudipinnis*	249.0	Na	0.0
Mirror dory	*Zenopsis nebulosa*	223.5	Na	0.0
Globefish	*Diodon nicthemerus*	183.3	Na	100.0
Gould's squid	*Nototodarus gouldi*	125.0	Na	0.0
Snapper	*Chrysophrys auratus*	121.0	Na	0.0
Roundsnout gurnard	*Lepidotrigla mulhalli*	101.8	472	100.0
Swordfish	*Xiphias gladius*	100.0	8	0.0
Miscellaneous teleosts	Na	85.0	Na	0.0
Silver trevally	*Pseudocaranx georgianus*	75.0	Na	0.0
Fiddler ray	*Trygonorrhina fasciata*	65.0	13	100.0
Blacktip cucumberfish	*Paraulopus nigripinnis*	61.4	Na	75.6
Gemfish	*Rexea solandri*	42.3	45	100.0
John dory	*Zeus faber*	37.1	Na	0.0
Unidentified shark	Na	32.5	5	15.4
Elephant fish	*Callorhincus millii*	32.0	8	100.0
Bigeye thresher shark	*Alopias superciliosus*	25.0	1	100.0
Eastern school whiting	*Sillago flindersi*	21.5	85	0.0
Royal red prawn	*Haliporoides sibogae*	19.7	Na	100.0
Rudderfish	*Centrolophus niger*	15.0	3	0.0
Jackass morwong	*Nemadactylus macropterus*	14.0	12	0.0
Spotted eagle ray	*Aetobatus ocellatus*	12.5	1	100.0
Silver Warehou	*Seriolella punctata*	10.0	41	0.0
Dog whelks	*Nassarius* sp.	8.0	35	100.0
Ornate angelshark	*Squatina tergocellata*	8.0	1	0.0
Spotted bigeye	*Priacanthus macracanthus*	6.3	22	0.0
Hermit crab	*Sympagurus* sp.	4.0	2	0.0
Mosaic leatherjacket	*Eubalichthys mosaicus*	4.0	2	0.0
Blue morwong	*Nemadactylus valenciennesi*	2.3	Na	0.0
Silver dory	*Cyttus australis*	2.0	2	0.0
Barracouta	*Thyrsites atun*	1.0	1	0.0
Giant boarfish	*Paristiopterus labiosus*	1.0	1	0.0



Supplementary Fig. 1. Plots of catch proportion curves showing the proportion of the combined catch from the 4- and 7-inch ground gears that was caught in the 7-inch ground gear. (a) falseband whiptail, *Coelorinchus maurofasciatus*, (b) smooth whiptail, *Malacocephalus laevis*, and (c) tiger flathead, *Platycephalus richardsoni*. The grey shading shows 95% confidence intervals for the catch proportion at each length.



Supplementary Fig. 2. Plots of catch proportion curves showing the proportion of the combined catch from the 7- and 10-inch ground gears that was caught in the 10-inch ground gear. (a) falseband whiptail, *Coelorinchus maurofasciatus*, (b) smooth whiptail, *Malacocephalus laevis*, and (c) tiger flathead, *Platycephalus richardsoni*. The grey shading shows 95% confidence intervals for the catch proportion at each length.

Appendix 6. Broadhurst, M.K. and Millar, R.B. 2022. Validating a narrow codend cover and improving selectivity in south-eastern Australian fish trawls targeting eastern school whiting, *Sillago flindersi*. Fish. Res. 251, 106302. doi:10.1016/j.fishres.2022.106302.

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Validating a narrow codend cover and improving selectivity in south-eastern Australian fish trawls targeting eastern school whiting, *Sillago flindersi*

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ABSTRACT

As part of attempts to improve selection among south-eastern Australian benthic fish trawls, an experiment was done to assess: (1) for confounding effects of a narrower-than-recommended hooped cover over a conventional trawl codend; and then (2) the associated size selection of eastern school whiting, *Sillago flindersi*; and (3) if this could be improved by inserting a large panel of smaller square-shaped mesh. The narrow cover was required to avoid contacting the seabed and did not affect trawl wing-end spread or catching efficiency. Despite a stretched mesh opening (SMO) of 96 mm and much larger than all *S. flindersi* (11–26 cm total length; TL), the conventional codend had a low 50% size at retention (L_{50}) of 16.8 cm TL (selection range of 5.9 cm), which was close to the minimum marketable length. The capture of small *S. flindersi* by the large-meshed codend was attributed to an excessive increase in circumference (from 100 to 200 meshes) and a legally permitted 'catch-separating' rope to restrict fractional mesh openings to <~21%. Replacing ~1/4 of the 96-mm SMO netting in the codend and anterior extension with a panel of square-shaped mesh (~42-mm SMO hung on the bar) marginally ($p = 0.065$) improved size selection for *S. flindersi* (by allowing some fish <~15 cm TL to escape). Increasing the size of mesh in the panel to ~47 mm hung on the bar might allow more smaller *S. flindersi* to escape. But using a smaller mesh size throughout the entire codend, concurrent with other gear or spatio-temporal controls when targeting *S. flindersi* might be a more coherent management option than retroactively handicapping the existing large-mesh codends.

1. Introduction

Benthic otter trawls are used globally to target a plethora of species contributing towards nearly 1/4 of the world's total marine harvest (Cashion et al., 2018). However, none of the configurations used are 100% selective and variable quantities of unwanted catches are often discarded (Cashion et al., 2018). Historical recognition of the deleterious ecological consequences associated with high discard mortalities has maintained consistent efforts at improving trawl selection, and mostly via modifications to the posterior sections, including the extension and codend, to increase lateral-mesh openings and/or install physical devices designed to separate unwanted catches (reviewed by Broadhurst, 2000; Kennelly and Broadhurst, 2021).

There are two methods for assessing the selectivity of modified codends/extensions (Millar and Fryer, 1999). The first involves alternately or simultaneously (via paired gear) deploying treatment codends/extensions attached to a conventional trawl, including small-meshed controls (~50% of the treatment mesh size; Wileman et al., 1996). The second, and most common approach, involves installing small-meshed covers over the codend/extension to retaining escaping organisms (Kennelly and Broadhurst, 2021). Covers are often preferred because fewer deployments are required to achieve statistical rigour for estimating size selection (Millar and Fryer, 1999).

Notwithstanding their utility, covering the codend/extension represents a substantial departure from conventional fishing. To limit confounding effects on trawl performance, there are recommended

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technical specifications including a mesh size as above and minimum cover diameters (maintained by hoops or kites) and lengths of 1.5 × and 2 × the codend/extension (Wileman et al., 1996; Madsen et al., 2001). However, within these criteria, variable fishery-specific characteristics encompassing different designs of trawls and their operation and/or modifications necessitate considerable diversity among cover designs. Ideally for particular trawls and operations, covers should be first validated for no confounding biological or technical effects that can include masking of meshes (affecting the escape of fish) or even reduced wing-end spread of the trawl—all of which can produce variable selectivity estimates (Madsen et al., 2001; Madsen and Holst, 2002).

One region where covers have not been routinely used to assess otter-trawl size selectivity (but alternate hauls have) is off southern Australia (but see Hunt et al., 2014), where some 40 vessels target numerous ground fish species mostly from Newcastle (32.82°S; 152.18°E) in New South Wales (NSW) around to the Great Australian Bight (34.09°S; 124.92°E), South Australia. Operators are managed under variable state and/or federal jurisdictional requirements, although all use single trawls, mostly with headline lengths of 25–45 m attached to sweeps and bridles ~150–200 m long (and spread by steel vee otter boards) with mesh sizes of 90–120 mm stretched mesh opening (SMO). Many vessels do not have stern ramps to retrieve the codend. Rather, operators typically have the net drum close to the transom and then move the codend to the side of the hull for retrieval midships. This configuration limits the working space aft, and especially with regards to deploying and retrieving a cover.

Historical concerns over unwanted bycatches by southern Australian fish trawlers have precipitated various studies (mostly alternate haul) aimed at quantifying and/or improving selectivity (e.g. Broadhurst and Kennelly, 1995; Graham et al., 2009). One sector of the fishery that has received particular attention involves vessels working inshore off NSW, which are required to use codends made from ≥ 90 mm SMO, that were traditionally ~20–33 meshes long (i.e. normal direction; N) by 100 meshes in circumference (transverse direction–T) and attached to an extension section 100 T × 100 N. Such configurations are appropriate for some targeted species (e.g. eastern blue-spotted flathead, *Platycephalus caeruleopunctatus* which have a minimal legal length–MLL of 33 cm total length–TL), however the mesh size is too large for another important fusiform species, eastern school whiting, *Sillago flindersi* which grow to only ~28 cm TL. Although *S. flindersi* are not subjected to a MLL, they are targeted at a minimum marketable length (MML) of ~17 cm TL. Very few *S. flindersi* are retained in the traditional 100 T codends.

Legal modifications to facilitate retaining *S. flindersi* are to reduce codend lateral-mesh openings by doubling the circumference to 200 T and also threading a single length of rope (≥3.4 m, termed a 'catch-separating' rope) throughout meshes around the codend midpoint to facilitate retrieval. Nevertheless, lateral mesh openings remain variable at ~35 to ~25% of the SMO, which affects selection (Graham et al., 2009). Mesh openings in a trawl codend should be configured to match the sizes and shapes of the smallest key target species, and in many cases smaller square-shaped or T90 meshes can benefit because they maintain more consistent lateral openings (e.g. Robertson and Stewart, 1988; Millar and Walsh, 1992; Kopp et al., 2018). But there is legislative resistance to alter the minimum mesh size of 90-mm SMO for NSW fish trawlers. A compromise might be to maintain the existing mesh size and install appropriate openings at strategic locations to allow small *S. flindersi* to escape, and more specifically a square-mesh panel made from smaller mesh hung on the bar (shown to be most effective for controlling the size selection of *S. flindersi* (Broadhurst et al., 2006).

Considering the above, our aims here were two-fold. First, we sought to test the hypothesis of no effects of a cover on the catching and engineering efficiency of a conventional fish trawl targeting *S. flindersi* and whether the estimated selectivity parameter vectors differ to those derived via an alternate-haul approach. Second, we aimed to determine if a modified conventionally configured codend comprising a square-mesh panel made from smaller mesh hung on the bar was more efficient at allowing small *S. flindersi* (<~17 cm TL) to escape.

2. Methods

The experiment was done during conventional fishing over five nights off Ulladulla, NSW (37.35° S; 150.46°E) across inshore otter-trawl grounds (~2.5 × 35 km area) between 27 July and 4 August, 2021 using a chartered trawler. The trawler was rigged with its conventional fish trawl (26-m headline) comprising nominal 90-mm SMO (polyethylene–PE) throughout attached to 27-m bridles and 185-m sweeps (20-mm diameter–Ø combination rope) and spread by steel V otter boards. A ~4.5-m extension section (100 T × 45 N) was attached at the end of the posterior trawl body and configured to enable different codends and a cover to be attached (Figs. 1 and 2 and below). The trawler was also equipped with a Notus trawl-monitoring system to measure wing-end spread (m) at the trawl and a Lowrance global positioning system (GPS) to record the distance travelled (m) and speed over the ground (SOG in ms^{-1}).

2.1. Codends, extensions and cover

Prior to constructing the codends and cover, 20 replicate meshes in each netting panel (i.e. type and size of mesh used) were measured for their wet (soaked in water for two hours) SMO. Replicate measurements of panel mesh sizes were repeated after the trial had finished. Two codends with short extension sections, and a codend/extension cover were built for the work. Both codend/extension sections were made from the same green 5-mm Ø braided PE netting and mesh size (~96-mm SMO; see Results); but differed in the presence/absence of square-mesh panels (Fig. 1). The first codend was a conventional diamond-mesh design measuring 200 T × 20 N and attached to a short extension section measuring 100 T × 15 N (Fig. 1a). The second design (termed the 'square-mesh panel codend') was identical, except the top ~1/4 of the codend (48 T × 18 N) and short extension (24 T × 10 N) were removed and replaced with 60 × 80 and 30 × 40 bars (B) of 42-mm PE mesh (Fig. 1b and c).

Each codend had a legally permitted catch-separating rope (3.4 m long and 4-mm Ø polyamide–PA) at the centre (i.e. at 10 N) effectively restricting the Ø at that point to ~1 m and a fractional mesh opening of ~17% SMO (Fig. 1). Another 3.4-m length of rope (4-mm Ø polypropylene; PP) was secured at one end of the last row of meshes in the short extension section and used to secure (by threading through meshes) each codend/extension to the main 4.5-m extension section on the trawl (Fig. 2a).

Following Wileman et al. (1996), a cover was constructed from 47-mm SMO netting (1.4-mm Ø PE twine) and measured twice as long as the extension/codend. Wileman et al. (1996) stated that for a codend with ~95–100 mm SMO and 100 T, the cover should have a Ø of ~2.5 m to achieve 1.5 × the fishing circumference (accounting for the shape of the codend). The codends tested here were 200 T, but the catch-separating rope restricted the centres to only 3.4 m circumference or ~1 m Ø. The diameter of the posterior codend remains unknown, but would presumably have a fractional mesh opening of ~25% or lower throughout at least some of its length (Robertson, 1986). This equates to a circumference of ~5 m or ~1.6 m Ø. Therefore, as a starting point, we hypothesised the cover might require a hooped circumference of 7.5 m or 2.4 m Ø. We initially configured two 60-mm poly-vinylchloride (PVC) hoops at 2.4-m Ø that could be attached to the cover by threading them through 150-mm Ø polyamide (PA) rings (n = 15), allowing the covers to be removed during deployment and retrieval (with couplings at the ends) (Fig. 2a and Wileman et al., 1996). However, during initial deplyments the hoops contacted the seabed and were progressively reduced to 1.6 m Ø, and with only one hoop at the codend (see Results; Fig. 2b).

The anterior edge of the cover had a selvage that could be threaded

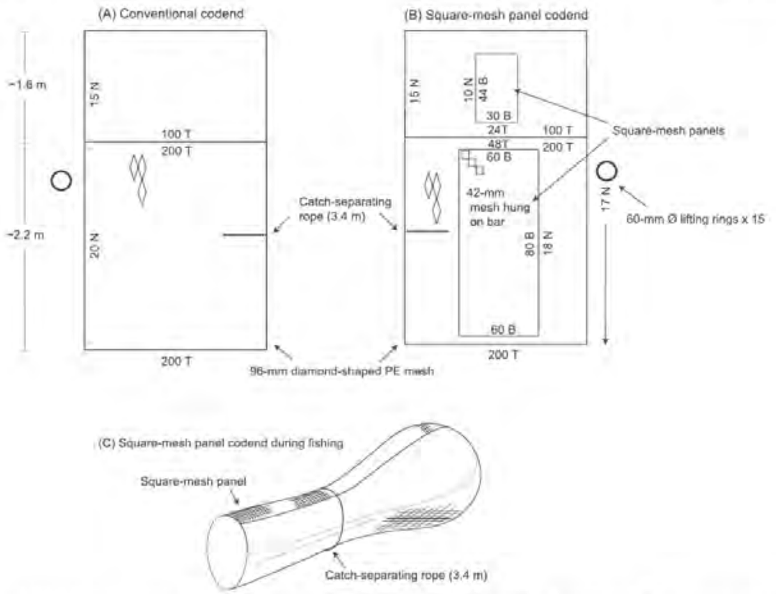

Fig. 1. Schematic diagrams of (a) conventional and (b and c) square-mesh panel codends tested during the experiment. T, transversal meshes; N normal meshes; B, bars; PE, polyethylene; and Ø, diameter.

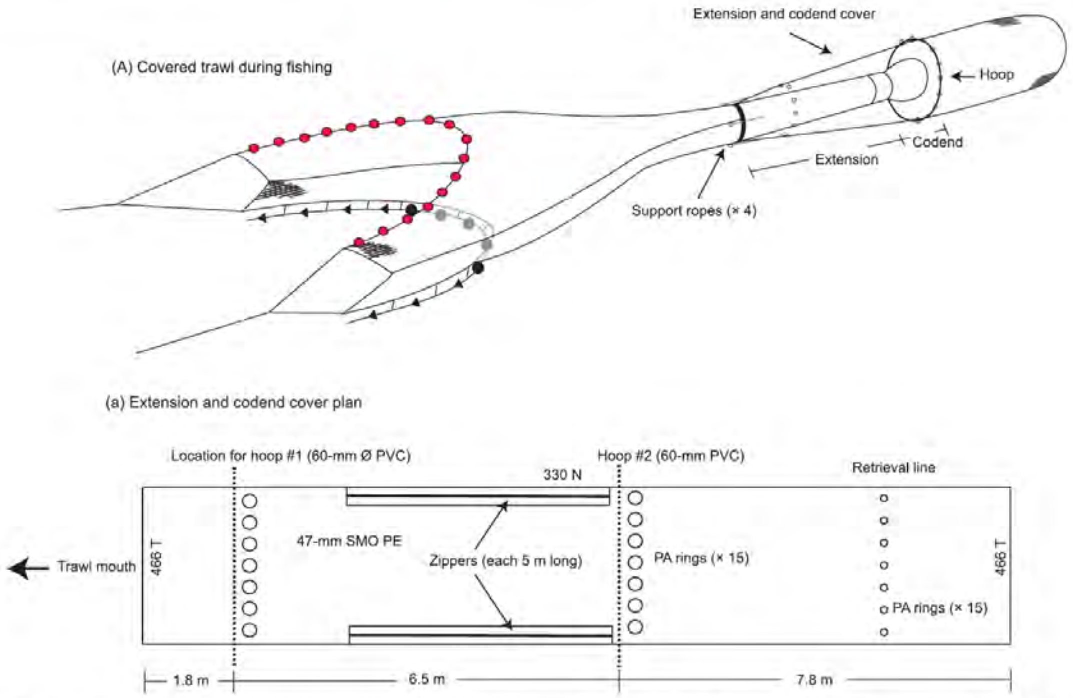

Fig. 2. (a) Three-dimensional representation of the cover during fishing and (b) two-dimensional plan. T, transversal meshes; N normal meshes; B, bars; PE, polyethylene; PA, polyamide; and Ø, diameter.

around the start of the anterior extension using a 3.4-m length of 4-mm Ø PP rope and four 1-m support ropes made from 4-mm Ø Dynema™ that were clipped using screw carabiners to four 60-mm Ø PA rings sewn to the anterior extension (Fig. 2a). Two 5.5-m long zippers (Buraschi S146R) were inserted along the sides of the cover (aligning with the codend) to facilitate removing the codend from the cover during retrieval onboard the vessel (Fig. 2b).

2.2. Sampling and data collected

On each night of fishing (18:00–0700), we attempted six consecutive deployments (depths of 24–77 m), comprising two replicate 50-min deployments (typical of conventional practices) of the conventional codend with and without the cover attached, and the square-mesh panel codend (without the cover attached). During each deployment, the start and end times (otter boards on and off the bottom) and depths, total distance trawled (from the GPS plotter), average SOG, and wing-end spreads (using the Notus trawl-monitoring system) were recorded.

Total catches were emptied into compartments on the deck (with known volumes) partitioned according to codend or cover (as required) and the total weights were calculated. For each partitioned catch, individuals of *S. flindersi*, *P. caeruleopunctatus* and tiger flathead, *P. richardsoni* were separated into retained and discarded categories (and placed into 30 l plastic crates) based on their MML or MLL, before being counted and weighed. Depending on the quantities, either all fish, or random subsamples of up to ~200 individuals deployment^{-1} from randomly selected crates were measured to the nearest 0.5 cm TL. The numbers and weights of other dominant, commercially important species, and weights of broader groups in catches from the codends were also recorded.

2.3. Statistical analyses

An assumption of no changes in mesh size within panels between the start and end of the experiment was assessed using a linear model (LM). Relevant technical data (wing-end spreads and area trawled) and biological data (numbers and weights of key species/groups in the codends) collected during the experiment were assessed using linear-mixed models (LMM). These latter models included the fixed effects of 'codend configuration' (three levels) and the random effect of 'days'. For wing-end spread, additional covariates included depth and SOG. Catches were standardised to ha^{-1} trawled (derived by multiplying average wing-end spread by the distanced trawled) and log-transformed (to act multiplicatively). Models were fitted using the glmmTMB function from the R package of the same name.

The size frequencies of *S. flindersi* in the codends and the cover (when attached to the conventional codend) were combined across all tows, stacked (with their scaling factors) and size-selection curves were attempted using maximum likelihood. A covered-codend approach (Wileman et al., 1996) was applied to relevant hauls (i.e. the covered-conventional codend). Subsequently, these catches (codend and cover) were then pooled to provide a 'control' for the uncovered square-panel and conventional codends fished as alternate hauls. For the latter, we used the estimated-split SELECT model for trouser trawls (Millar and Walsh, 1992). The covered-codend and alternate-hauls models were fitted using the SELECT function within the R package of the same name (Millar, 2021).

The choice of selection curve (logistic or Richard's) was made by assessing residual plots and fits confirmed via visual examination of deviance residuals and by comparing adjusted model deviances and associated degrees of freedom with a chi-squared distribution (Millar and Fryer, 1999). The model deviances were adjusted for over-dispersion due to between-haul variation using the replicate estimate of dispersion (Millar and Fryer, 1999). Confidence intervals for the parameters of interest (50% probability of retention; L_{50}, and selection range; SR) for the best model were obtained using a double bootstrap to incorporate both between- and within-haul variabilities. Ten thousand bootstrap simulations were performed. Pointwise 95% confidence intervals for the retention probability at any given length were similarly obtained.

Relative size frequencies of *S. flindersi* were also explored for a statistically significant difference between the uncovered conventional and square-panel codends using a permutation test (Broadhurst and Millar, 2009). This was done by first using the SELECT method to fit a logistic selection curve to the proportions at length retained in the square-panel codend given retention in the uncovered conventional or square-panel codends. The observed likelihood ratio test statistic (LRT) for a difference between codends was then compared to the distribution of the LRT obtained from randomly permuting the hauls of these two gears so as to reallocate the hauls amongst the two gears. Ten thousand permutation resamples were performed.

The above permutation procedure was then repeated to test for a difference between the uncovered conventional and covered conventional codends, as a further validation check that the cover was not having a significant effect on selectivity of the conventional codend. All analyses were done in R (R Core Team, 2021).

3. Results

The average (± SE) SMOs in the PE netting panels used to make the codends, square-mesh panel and cover prior to fishing were 95.8 ± 0.3, 42.4 ± 0.3 and 47.4 ± 0.3 mm, respectively. Post-fishing, random measurements of SMO within the panels of the netting used were not significantly different at 95.7 ± 0.3, 42.3 ± 0.3 and 47.2 ± 0.2 mm, respectively (LM, $p > 0.05$).

There were technical issues with the first two deployments of the covered-conventional codend (first night), with both the 2.6-m and then 2.1-m Ø hoops contacting the seabed and being broken on retrieval. The front hoop was removed because it complicated retrieving the trawl and instead, a single 1.6-m Ø hoop was used at the codend for subsequent deployments, and without any further technical issues (Fig. 2a). One and two deployments of the uncovered conventional and square-panel codends were also excluded owing to onboard technical issues, and to better balance replication, a substituted third deployment of the latter was done on the last night. During several deployments of the square-panel codend, some *S. flindersi* and another fusiform species, yellowtail scad, *Trachurus novaezelandiae* were observed impinged in the square-mesh panel.

In total, 25 deployments were completed (eight replicates each of the covered/uncovered conventional codend and nine replicates of the square-panel codend) for a total catch of ~15.2 t, comprising >19 species of mostly economically important teleosts (~9.4 t), eight species of elasmobranchs (~5.7 t) and four species of cephalopods (~0.1 t) (Table 1 and Stable 1). The key teleosts *S. flindersi*, *P. caerulopunctatus* and *P. richardsoni* comprised 21.0, 3.8 and 2.4%, respectively of the total catch, and with 87, 67 and 17%, ≥ MML or MLL (Table 1). Approximately 1.4 t was retained in the cover, including 690, 35 and 61 kg of the three species above.

3.1. Analyses of wing-end spread, area trawled and numbers and weights of catches

Linear mixed models failed to detect any significant effects of depth, SOG or codend configuration on the wing-end spread of the trawl, with average predicted (± SE) values of 10.6 ± 0.1, 10.3 ± 0.1 and 10.3 ± 0.1 m when attached to the conventional codend without and with the cover, and the square-panel codend ($p > 0.05$). But, because of the variation in mean wind-end spreads and deployment durations (42–55 min), there was a significant difference in the ha trawled, with predicted means of 5.0 ± 0.2, 4.5 ± 0.2 and 4.9 ± 0.2 ha for the three configurations (LMM, $p > 0.05$).

After adjusting for multiple comparisons (Benjamini and Hochberg,

Table 1
Common and Latin names of species and groups and their numbers, weights (kg) and size ranges (where measured for total length–TL in cm) caught in the codends (not the cover) during the experiment, with the percentage of eastern school whiting ≥ 17 cm TL (minimum marketable length; MML) and legal-sized individuals of those species with minimum legal lengths (MLL) in parentheses. ^economically important species. Na, not available.

Group	Latin name	Total no.	Total wt (% ≥ MML or MLL)	TL range
Teleosts	Eastern school whiting^, *Sillago flindersi*	63,275	3238.0 (87)	11.0–26.0
	Eastern blue-spotted flathead^, *Platycephalus caeruleopunctatus*	2255	589.0 (67)	20.0–58.0
	Tiger flathead^, *Platycephalus richardsoni*	3952	359.0 (17)	16.0–49.0
	Yellowtail scad^, *Trachurus novaezelandiae*	Na	~3000	Na
	Red gurnard^, *Chelidonichthys kumu*	Na	~700	Na
	Blue-lined goatfish^, *Upeneichthys lineatus*	44	6.7	Na
	Common conger eel, *Conger wilsoni*	1	1.5	Na
	Blue morwong^, *Nemadactylus valenciennesi*	1	1.0	Na
	Ocean jacket^, *Nelusetta ayraud*, redfish^, *Centroberyx affinis*, flounders^., *Pseudorhombus* spp., barracouta, *Thyrsites atun*, grey morwong^, *Nemadactylus douglasii*, spotted bigeye, *Priacanthus macracanthus*, sergeant baker, *Latropiscis purpurissatus*, redbait^, *Emmelichthys nitidus*, john dory^, *Zeus faber*, silver trevally^, *Pseudocaranx georgianus*, and blackspot boarfish, *Zanclistius elevatus*	Na	~1500	Na
Elasmobranchs	Australian angelshark^, *Squatina australis*, southern eagle ray, *Myliobatis tenuicaudatus*, common stingaree, *Trygonoptera testacea*, sparsely spotted stingaree, *Urolophus paucimaculatus*, Port Jackson shark, *Heterodontus portusjacksoni*, eastern fiddler ray^, *Trygonorrhina fasciata*, and eastern shovelnose ray^, *Aptychotrema rostrata*	5603	5614	Na
	Sevengill shark^, *Notorynchus cepedianus*	1	60.0	Na
Cephalopods	Gould's squid^, *Nototodarus gouldi* and southern calamari^, *Sepioteuthis australis*	192	65.7	Na
	Rosecone cuttlefish^, *Sepia rozella*	225	40.0	Na
	Maori octopus^, *Octopus maorum*	2.0	1.2	Na

1995) there were no significant differences in weights of catches ha^{-1} trawled for the total or any species between the conventional (covered or uncovered) and square-panel codends (overall p-value >0.4). Mean catch weights remained similar; albeit with considerable variability, especially for *P. caeruleopunctatus*, *P. richardsoni* and *T. novaezelandiae* (Fig. 3b, c and e).

3.2. Analyses of size selectivity

There were too few *P. caeruleopunctatus* and *P. richardsoni* retained in the cover (i.e. only 35 and 61 kg) to enable attempts at size-selection curves. Sufficient data were available for *S. flindersi* to converge parametric selection curves for the covered conventional codend, with a logistic model preferred (STable 1; Fig. 4a). This model estimated an L_{50} of 16.8 cm TL with 95% CI of 14.6–17.9 mm and close to the MCS (17 cm TL), but with a very wide SR of 5.7 cm bounded by CI of 4.2–10.8 cm (Fig. 4a).

Excessive between-haul variability in sizes of *S. flindersi* precluded coherent selection curves via alternate haul for either the uncovered conventional or square-panel codends. The permutation test between these codends returned a non-significant p-value of 0.065, but with evidence of proportionally fewer *S. flindersi* < 15.0 cm TL and more between 16.5 and 18.0 cm TL retained in the uncovered square-panel than conventional codend (Fig. 4b). The permutation test between covered and uncovered conventional codends showed no significant difference in size selectivity, returning a p-value of 0.45 (Fig. 4c).

4. Discussion

The data here support two broad conclusions. First, it is evident that for the targeted species, *S. flindersi* a substantially narrower cover than traditionally recommended can produce a coherent selection curve and, like for overseas studies with other species, less variability than an alternate-haul approach when replication is low (Sistiaga et al., 2009). Second, it is clear the conventional diamond-mesh codend used in this fishery is not entirely appropriate for the targeted sizes of *S. flindersi*, but like for many other trawls there is evidence performance could be improved by simply inserting a relatively small panel of square-shaped mesh with a mesh size matching the required species morphology (e.g. Madsen et al., 2002; Tokaç et al., 2010; Sistiaga et al., 2018). These conclusions can be discussed by considering the operation of the trawl and the morphology and probable behaviour of *S. flindersi* and used to suggest future gear refinements.

The narrow cover tested here neither affected the wing-end spread of the trawl nor catching efficiency for the various species and groups including weights and sizes of the key target, *S. flindersi*, implying minimal or none of the so-called 'masking effects' which can arise through poor cover design or configuration (Madsen and Holst, 2002). There are various options for configuring covers to remain clear of the contained codend/extension, including kites (Cheng et al., 2019), combinations of kites, floats and chains (Madsen et al., 2001, 2002; Madsen and Holst, 2002; Kopp et al., 2018) or simply two (Kynoch et al., 2004; Jørgensen et al., 2006; Brčić et al., 2018) or more solid hoops (Broadhurst et al., 2010). Less frequently, a single hoop has been used, either well anterior to the codend and with additional posterior floats (e.g. Dahm et al., 2002) or around the centre of the codend (Dereli and Aydin, 2016; present study). Unlike kites which require known and fixed circumferences of covers and presumably create additional drag (which could affect the geometry of small trawls), hoops allow a cover circumference to be adjusted among trawls and might be more applicable for variable small, low-opening designs.

Despite being much narrower than the configuration recommended by Wileman et al. (1996), the cover tested here provided coherent results and its single hoop design facilitated a fairly rapid removal/attachment at the vessel stern, allowing the entire assembly to be moved to the side of the vessel within similar time frames as without.

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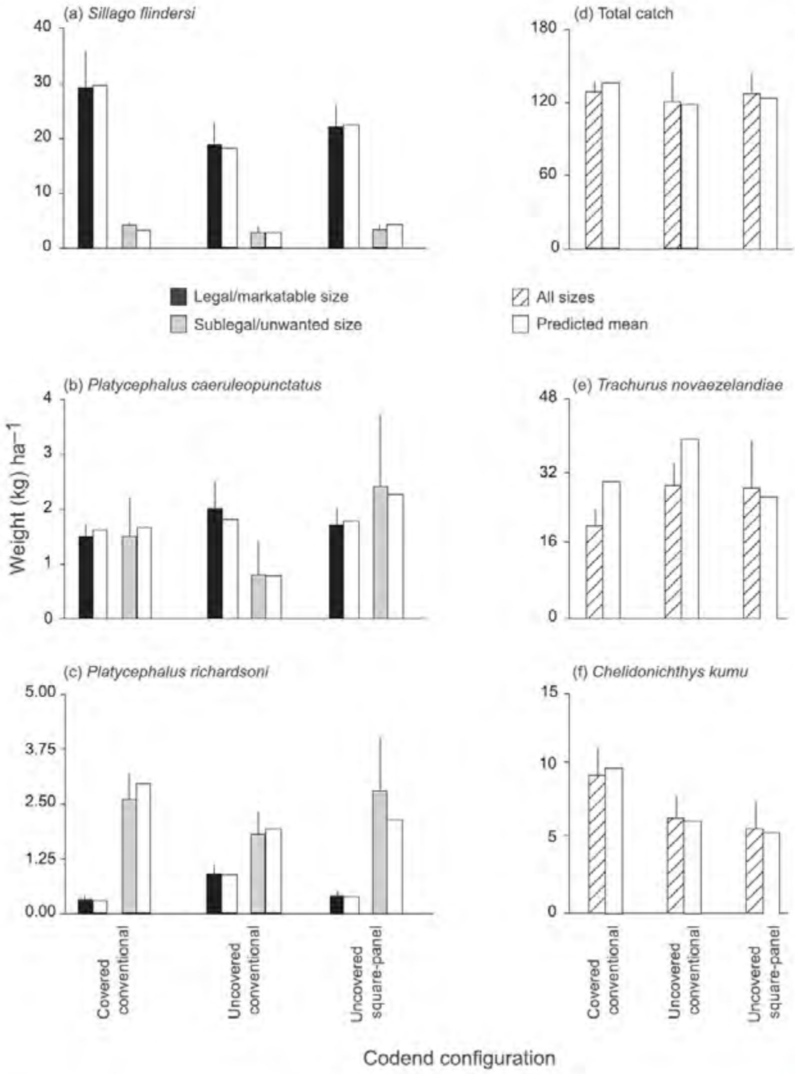

Fig. 3. Differences in raw (± SE) and predicted mean weights ha^{-1} between the covered and uncovered conventional codend and uncovered square-panel codend for (a) marketable (≥17-cm total length; TL) and unwanted sizes (<17 cm TL) of eastern school whiting, *Sillago flindersi*, and legal (≥33 cm TL) and sublegal (<33 cm TL) (b) eastern blue-spotted flathead, *Platycephalus caeruleopunctatus* and (c) tiger flathead, *Platycephalus richardsoni*, and total (d) catch, (e) yellowtail scad, *Trachurus novaezelandiae*, and (f) red gurnard, *Chelidonichthys kumu*.

These results suggest that narrow-circumference covers might have utility among other benthic trawls, but the hypothesis of no confounding effects on engineering or catching performances still warrant fishery and species-specific assessments. Such hypotheses are rarely addressed and might not be required for covers meeting the specifications of Wileman et al. (1996) or Madsen and Holst (2002), but perhaps should be prioritized for substantial technical departures. The same logic might apply to other designs of small covers over physical bycatch reduction devices, which are almost never validated (reviewed by Kennelly and Broadhurst, 2021).

Notwithstanding the need to validate covers on trawls, an important consideration is that irrespective of the potential for any masking effects of the codend during fishing, these could be confounded by the escape of broader sizes of key species at the surface during hauling and, in the present study, the transfer of the codend to the vessel side. Previous studies have shown fish of variable sizes can escape from codends during hauling and then at the surface, as towing speed reduces and lateral mesh openings increase (Broadhurst et al., 1996; Grimaldo et al., 2009). Here, irrespective of the cover, the large codend meshes were observed to open and close with the surging swell as the configuration was transferred to the side of the vessel, and potentially this might have increased the escape of small species like *S. flindersi* and *T. novaezelandiae*.

While it is likely that there is variable size selection of *S. flindersi* during each of trawling, hauling and then at the surface, it is clear that the existing conventional codend is not appropriate for the species. The L_{50} (16.82 cm TL) of *S. flindersi* here was lower than those (18.69–22.69 cm fork length; FL or ~20–25 cm TL) estimated by Graham et al. (2009) for codends with comparable mesh sizes (90-mm SMO; albeit slightly narrower twine at 4-mm Ø) and the same circumference; but the wide SRs remained the same (5.86 cm here vs 5.17–6.46 cm). The lower L_{50} might partially reflect the different twine Ø and/or testing procedures (covered codend vs alternate haul; Sistiaga et al., 2009), although a major modification here was the catch-separating line at

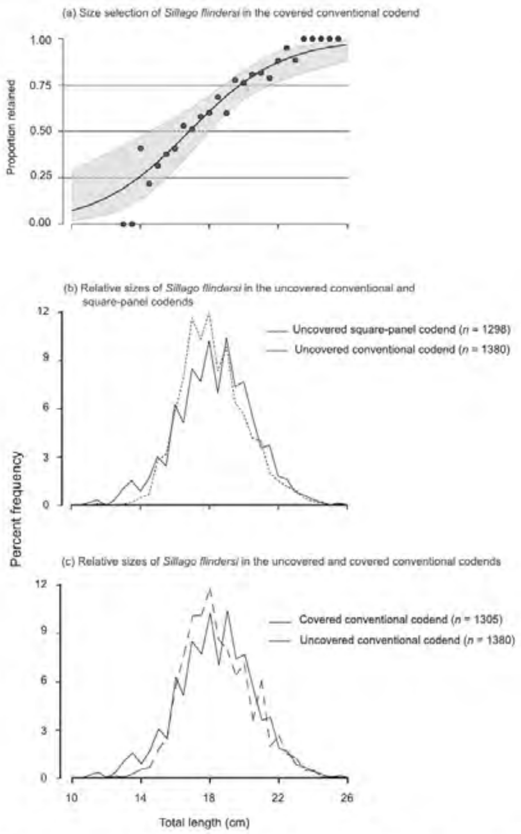

Fig. 4. Summaries of analyses of size (total length in cm) data for eastern school whiting, *Sillago flindersi*: (a) proportions of retained and the logistic curve (bound by 95% confidence intervals as shaded) for individuals in the covered conventional codend; and scaled-up percent frequencies of measured sizes (stated with 'n') retained in the (b) uncovered square-panel and conventional codends, and (c) covered and uncovered conventional codends.

3.4 m, which would have minimised lateral-mesh openings throughout at least some of the codend, especially anterior to the accumulating catch. Other studies have shown various similar codend attachments, including strengthening bags of chafing gear can similarly restrict lateral openings and preclude the escape of some small fish (Kynoch et al., 2004). Considering a *S. flindersi* at the L_{50} of 16.82 cm TL has an average maximum height and width of ~29 and 20 mm (Broadhurst et al., 2006) the large circumference and catch-separating line here were clearly sufficient to cumulatively reduce fractional mesh openings throughout the 96-mm meshes to ~21%.

Adding the square-mesh panel neither significantly affected the catch weights nor sizes of *S. flindersi*, but the permutation test provided some evidence of relatively greater proportions of the smallest *S. flindersi* escaping. The square mesh had a perimeter of ~85 mm, which in terms of girth corresponds to a *S. flindersi* of ~15 cm TL. The escape of fish up to this size was supported by several individuals observed meshed in the panel on retrieval, and also previous work which demonstrated small *S. flindersi* actively attempt escape via such panels in other trawls (Broadhurst et al., 1996, 2002). A slightly larger mesh size (e.g. 47–48 mm hung on the bar) should allow fish up to 17 cm TL to escape. Certainly, fish ~15–17 cm TL were common in codend catches, and their abundance might facilitate future detection of any size differences due to a square-mesh panel made from larger mesh.

Platycephalids have also been noted to escape though anterior square-mesh panels in the tops of codends, implying some species will swim upwards in the extension and actively attempt mesh penetration (e.g. Broadhurst et al., 2002). However, the square-shaped meshes here were much smaller than the smallest platycephalid, precluding any significant reductions in their numbers. Conversely, the absence of any significant increase in numbers or weights of undersized individuals in the square-panel codend might imply the relatively small area of the panel relative to the total codend/extension surface area means for the few that escaped, they had opportunity to do so through the remaining larger 96-mm meshes.

While the square-mesh panel marginally improved size selection, a better option might be to remove the catch-separating rope and consider using a smaller mesh size (either diamond-, square-shaped or T90) throughout the codend and appropriate circumferences to maximise lateral openings. Additionally, the use of such a codend might be controlled via defined spatial deployments (i.e. among areas designated for *S. flindersi*). There are complex gear-specific differences in mesh size for this species. Danish seiners working further south off Victoria are permitted a minimum mesh size of 38 mm (at an appropriate circumferences) when targeting *S. flindersi* while Danish seiners and penaeid trawlers working further north in NSW can use minimum mesh sizes of 83 (and excessive circumferences) and 40 mm (typically with appropriate or slightly increased circumferences), respectively (Broadhurst and Kennelly, 1996). A coherent starting point for mesh size in any fishery is to select that which is most appropriate for the morphology of the smallest target species, before attempting incremental trawl improvements to refine selection. And, any trawl characterized by an increase in mesh circumferences at the codend indicates the SMO is too large for the desired species, and therefore warrants investigation (Kennelly and Broadhurst, 2021).

Considering the data here and the argument above, a smaller and more appropriately shaped mesh might be warranted for targeting *S. flindersi* by southern inshore fish trawlers in NSW. To avoid other unwanted fishing mortalities, it might be conceivable to designate specific areas for usage, and/or investigate other ancillary trawl modifications. One option for large elasmobranchs could involve grids with bar spaces sufficiently large enough to allow all commercially important teleosts to pass through to the codend (e.g. Broadhurst et al., 2005). But assessing any such modifications requires adequate consultation with fishers to address technical issues, and sufficient at-sea testing to support adoption prior to legislation (Kennelly and Broadhurst, 2021).

CRediT authorship contribution statement

Matt K. Broadhurst: Conceptualization, Data curation, Funding acquisition, Investigation, Methodology, Project administration, Resources, Software, Supervision, Validation, Visualization, Writing – original draft, Writing – review & editing. **Russell B. Millar:** Conceptualization, Formal analysis, Methodology, Software, Visualization, Writing – review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.fishres.2022.106302.

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STable 1. Summary of hauls completed with each codend configuration on each fished day and the total weights and numbers of eastern school whiting, *Sillago flindersi* caught, the numbers measured and the associated scaling factor to rise numbers to total catches.

			Eastern school whiting, *Sillago flindersi*			
Day	**Haul**	**Codend configuration**	**Total wt (kg)**	**Total no**	**No measured**	**Scaling factor**
29/07/2021	Five	Covered conventional	159.00	2902	111	26.14
		Cover	105.00	2163	120	18.06
29/07/2021	Six	Covered conventional	106.20	1988	121	16.38
		Cover	122.00	3233	92	35.14
30/07/2021	One	Covered conventional	246.90	4277	205	20.86
		Cover	83.00	1875	75	25.00
30/07/2021	Two	Covered conventional	342.60	6553	204	32.12
		Cover	103.00	2280	114	20.00
02/08/2021	Three	Covered conventional	99.10	1782	128	13.92
		Cover	130.00	3312	106	31.25
02/08/2021	Four	Covered conventional	88.20	2005	183	10.98
		Cover	67.00	1685	95	17.83
03/08/2021	Five	Covered conventional	133.70	2218	145	15.27
		Cover	64.00	1300	100	13.0
03/08/2021	Six	Covered conventional	58.60	1429	157	9.10
		Cover	17.00	404	101	4.00
27/07/2021	Three	Uncovered conventional	27.10	561	201	2.79
27/07/2021	Four	Uncovered conventional	68.20	1361	204	6.67
29/07/2021	Three	Uncovered conventional	67.00	984	117	8.41
29/07/2021	Four	Uncovered conventional	44.10	1173	179	6.55
30/07/2021	Three	Uncovered conventional	161.90	2865	194	14.77
02/08/2021	Five	Uncovered conventional	101.30	1816	171	10.62
02/08/2021	Six	Uncovered conventional	171.80	3110	130	23.92
03/08/2021	One	Uncovered conventional	215.40	4870	184	26.47
29/07/2021	One	Uncovered square-panel	48.80	1065	111	9.59
29/07/2021	Two	Uncovered square-panel	76.60	1452	104	13.96
30/07/2021	Five	Uncovered square-panel	251.50	5007	183	27.36
30/07/2021	Six	Uncovered square-panel	28.50	413	62	6.66
02/08/2021	One	Uncovered square-panel	156.70	2696	153	17.62
02/08/2021	Two	Uncovered square-panel	145.90	2833	156	18.16
03/08/2021	Two	Uncovered square-panel	184.30	3826	152	25.17
03/08/2021	Three	Uncovered square-panel	167.00	3553	195	18.22
03/08/2021	Four	Uncovered square-panel	87.50	2026	182	11.13

Appendix 7. Broadhurst, M.K., Knuckey, I.A. and Millar, R.B. 2022. Benefits of conventional anterior codend meshes turned 90º in an Australian trawl fishery are limited to an improved quality of *Neoplatycephalus conatus*. Fron. Mar. Sci. 9:951549. doi:10.3389/jmars.2022.951549

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Benefits of conventional anterior codend meshes turned 90° in an Australian trawl fishery are limited to an improved quality of *Neoplatycephalus conatus*

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Turning conventional diamond-shaped meshes 90° ('T90') in trawl extensions or codends is a simple modification for consistently increasing lateral openings and has improved size selection in several European fisheries. Here we investigate the effects of an industry-instigated cylinder of T90 meshes in the anterior codend of a trawl fished in the Great Australian Bight. Compared to the traditional codend (~5.4 m long) comprising a 93.5-mm stretched mesh opening (SMO) and double 4.1-mm-diameter twine throughout, the new T90 configuration comprising ~3 m of the same mesh turned 90° in the anterior section did not significantly affect catches of any discarded or retained species, or sizes of the primary target, deepwater flathead, *Neoplatycephalus conatus*. The only significant impact of T90 was a slightly improved quality of deepwater flathead (determined by the 'quality index method'), attributed to some release of abrasive debris from the codend. The absence of any effects of the T90 mesh on selection might reflect the small mesh size relative to most key species and the thick twine which probably negated some of the anticipated increases in lateral mesh openings. The results reiterate the need to match the mesh perimeter to the sizes of the key target prior to efforts at maximising lateral openings (*via* various established technical options), but nevertheless imply the benefits of T90 mesh may extend beyond selection.

KEYWORDS
bycatch reduction device, catch quality, fish trawl, selectivity, T90

Introduction

Demersal fish trawling is among the world's most common fishing methods, responsible for ~25% of the total ocean harvest (~98 m t; Pauly et al., 2020), but owing to poor selectivity, also ~30% of global discards (Pérez Roda et al., 2019). Concerns over the cascading effects of discard mortalities have evoked numerous efforts at improving fish-trawl selectivity, usually by modifying codends because this is where most selection occurs (Kennelly and Broadhurst, 2021).

Ideally, codend mesh openings should match the size/shape of the smallest targeted species. However, conventional diamond meshes ('T0') have inconsistent openings, which reach a maximum of ~35% of the stretched mesh opening (SMO) immediately in front of the catch, but then taper forward to 15%–25% of SMO (Robertson, 1986; Robertson and Stewart, 1988). Such variability often produces less-than-ideal size selection.

There are simple options for improving lateral mesh openings in codends. One method is to attach so-called 'lastridge' ropes along the codend/extension, usually at ~70%–95% of the total stretched length, forcing meshes to remain open (Robertson and Stewart, 1988; Ingólfsson and Bronkholf, 2020). Other methods are to turn some, or all, meshes in the codend to either 45° ('T45') or 90° ('T90') which forces wider and consistent lateral openings (Robertson and Stewart, 1988; Moderhak, 1997).

While effective, there are operational issues with alternative mesh orientations. Specifically, compared to T0 meshes, T45 meshes can distort and are weaker, while T90 meshes can eventually assume a diamond shape (although strength remains) (Madsen, 2007). Installing lastridge ropes along codends/extensions comprising either T45 (Broadhurst et al., 1999b) or T90 meshes (Einarsson et al., 2021) has minimised the above operational issues in crustacean trawls, implying utility among fish trawls, although there have been few studies (Kennelly and Broadhurst, 2021).

Anecdotal industry reports from an Australian fish-trawl fishery in the Great Australian Bight (10 fishing licences) suggest that compared to traditional codends comprising ~94-mm T0 mesh throughout (~55 meshes long × 100 meshes in circumference), substituting the anterior ~56% of the codend with four panels of the same 94-mm mesh turned 90° and with shortened lastridge ropes (by 17%) improves selection for the key target, deepwater flathead, *Neoplatycephalus conatus* (typically >35 cm TL). Further, by allowing sand and small abrasive debris to escape the codend, the T90 mesh reportedly reduces dermal damage to fish and improves their quality and price. However, no formal trials have been done to test either of the above assertions. The aims here are to address the deficit and test a four-panel, T90 anterior codend section with lastridge ropes against the traditional T0 codend.

Materials and methods

The experiment was done in the Great Australian Bight, Australia (33.12°S; 128.06°E to 33.27°S; 129.40°E), during 6 consecutive days and nights from 1 December 2021 using a trawler (35 m and 500 Kw) rigged with a conventional, single two-seam trawl (41-m headline, with nominal 152- and 120-mm SMO in the wings and body) attached to 20- and 200-m bridles and sweeps and spread by steel V-otter boards. The posterior body (100 meshes in the transverse direction–T) was configured to enable different extensions (larger-mesh section connecting the codend to the body) and codend sections (i.e., smaller-meshed bag where the catch accumulates) to be attached (below). The vessel had a Scanmar trawl monitoring system to measure otter-board spread, a Lowrance global positioning system (GPS) to record distance and speed over the ground (SOG), and a Furuno echo sounder for fishing depth.

Codends tested

Two identical extension sections, a T0 codend and a partial T90 codend, were each constructed from the same panels of braided knotted netting (green polyethylene; PE), which were measured for 15 replicate samples of SMO and twine diameter (Ø) to the nearest 0.1 mm using a purpose-built gauge and Vernier callipers, respectively (Figure 1). Both extensions and codends were the same total lengths and comprised four panels (with four lastridge ropes). The extensions had mean mesh sizes (± SE) of 105.5 ± 0.4 mm SMO (3.9 ± 0.0 mm Ø twine) and measured 24.5 meshes in the normal direction (N) and 100 T creating T0 meshes (Figure 1). Each extension had lastridge ropes (for strength) made from 24-mm Ø twisted polypropylene (PP) and the same lengths as the stretched meshes (Figure 1). A 3.4-m length of rope (4.0-mm Ø PP) was secured at one end of the last row of meshes in each extension to secure these to the posterior trawl body.

The two extensions were attached to either a traditional 'T0' or new 'T90' codend, both made from 93.5 ± 0.3 mm SMO with double 4.1 ± 0.0 mm Ø twine (Figure 1). The T0 codend measured 54.5 N × 100 T and had four lastridge ropes the same as those for the extensions (at the panel junctions) (Figure 1A). The T90 codend had a posterior section (24.5 N × 100 T) identical to the T0 codend but a different anterior section: comprising T90 (50 T × 66 N). Four lastridge ropes (16-mm Ø Dyneema™) extended throughout the codend and were 83% of the stretched T90 length (or ~60% of the traditional T0 SMO) in that section, and the same length as the T0 codend in the posterior section (Figure 1B).

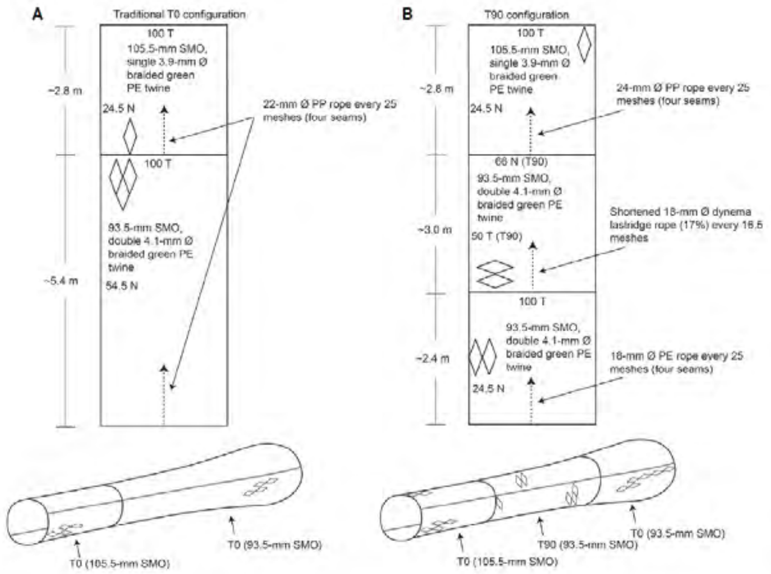

FIGURE 1
Schematic diagram of the (A) traditional T0 and (B) new T90 codends. Ø, diameter; N, normal direction; T, transverse direction; SMO, stretched mesh opening; PE, polyethylene; PP, polypropylene.

Sampling protocol and data collected

The two codend/extensions were alternately attached to the trawl and fished in pairings across similar depths and locations, providing four deployments (~3.5–5.0 h) every 24 h, during 6 days (i.e., 24 replicates). Technical data included swell height (m), fished location, distance (km) and duration (h; winch brakes on and off), otter-board spread (m); SOG (ms^{-1}), and depth (m) of the trawl. The latter three variables were logged every ~15 min to provide an average deployment^{-1}.

After retrieval, the codend was emptied into an area with a measured volume, and the total catch weight was estimated. Retained catches were separated and boxed before weighing and counting. The total weight of discarded catch (bycatch) was estimated by subtracting the retained component from the total catch. A subsample of discards was then assessed. All discards were then individually counted and weighed in the subsample and extrapolated to the total. Randomly selected subsamples of deepwater flathead (up to 115 deployment^{-1} or ~one-third of catches) were measured to the nearest 0.5-cm TL.

For most deployments, an additional 15 deepwater flathead were randomly selected (~45 to 55 cm TL) after being placed in boxes (deceased and prior to freezing) and assessed for physical damage using a version of the 'quality index method' (QIM) (Nielsen, 2005). For each sample, 11 qualitative measures (describing skin, scales, gills, fins, eyes, and wounds) were recorded and scored between 0 and 3, according to worsening severity (STable 1). The sums of the 11 scores for each fish were then used to provide a datum describing individual physical condition/quality.

Data analyses

Data for otter-board spreads and standardized (ha^{-1} trawled and log-transformed to act multiplicatively) catches (numbers and weights) were analysed using linear mixed models (LMMs). The QIM scores were approximately Gaussian and also analysed with LMMs. In all models, 'codend' was considered fixed while 'pairs' were random. Additional covariates of 'SOG' and fishing 'depth' were also assessed in the LMM assessing variability among otter-board spread, while 'total catch weight', depth, and 'tow duration' were used in the LMM assessing QIM data. The significance of terms was determined using likelihood ratio tests (Millar, 2011).

Relative size frequencies of deepwater flathead were explored for statistically significant differences between the codends by using the 'SELECT' (Share Each LEngths Catch Total; Millar, 1992) model to fit a cubic regression spline to the proportions at length of all retained fish that were retained in the trawl with the

T90 codend. This catch-comparison analysis was implemented using the SELECT R package which includes bootstrap functionality to allow for between-haul variability (Millar et al., 2004; Millar, 2021). A permutation test was also used (10,000 resamples) to assess for any statistical significance of codend configuration (Broadhurst and Millar, 2022). All analyses were done in R (R Core Team, 2021).

Results

The 24 replicate tows (3.4–5.0 h; mean ± SE of 4.8 ± 1.1 h) were at consistent SOG (3.0–3.4; 3.1 ± 0.0 ms^{-1}) and depths (112–148; 125.5 ± 3.0 m) and across comparable weather (mostly swell <0.6 m). Otter-board spread was not significantly affected by the codends tested (LMM, $p > 0.05$) but was significantly and positively influenced by fishing depth (LMM, $p < 0.05$).

In total, 58.5 t (>63 species) was caught, of which 19.1 and 39.4 t were retained and discarded, respectively; however, 74% of the latter was wide stingaree, ***Urolophus expansus*** (STable 2). Nine retained and three discarded species (92% of total catches) were caught in sufficient quantities to test for effects on their catches due to codends, but there were no significant differences among any of their weights or numbers (LMM, $p > 0.05$; Table 1).

Similarly, the permutation test established that the proportion of the total catch (combined over the T0 and T90 codends) of deepwater flathead (32.5–80.0 cm TL, but mostly 40.0–50.0 cm TL) caught in the T90 codend did not depend on TL. That is, there was no significant difference in the size selection of deepwater flathead due to codend (p = 0.7; Figure 2).

The only significant effect of codend was restricted to log-transformed QIM scores for deepwater flathead ($p < 0.05$). The parsimonious model eliminated effects of total catch or SOG and revealed a significantly lower score among those fish caught in

TABLE 1 Summary of catches (and their totals) tested in mixed-effect models assessing the importance of codend configuration and the means ± SE ha^{-1} trawled separated for the T0 and T90 codends.

Variable		**Mean (± SE) ha^{-1} trawled**	
Retained catches	**Total amount**	**T0 codend**	**T90 codend**
Wt of total	19,123.8	1.85 (0.15)	1.87 (0.18)
Wt of deepwater flathead, *Neoplatycephalus conatus*	6,910.0	0.74 (0.03)	0.59 (0.06)
No. of deepwater flathead	9,006	0.97 (0.07)	0.78 (0.09)
Wt of latchet, *Pterygotrigla polyommata*	3,213.9	0.27 (0.10)	0.33 (0.13)
No. of latchet	12,342	1.05 (0.45)	1.24 (0.56)
Wt of gummy shark, *Mustelus antarcticus*	1,995.8	0.23 (0.10)	0.20 (0.07)
No. of gummy shark	691	0.09 (0.05)	0.06 (0.02)
Wt of ocean jacket, *Nelusetta ayraudi*	1,624.5	0.17 (0.06)	0.15 (0.08)
No of ocean jacket	2,904	0.27 (0.10)	0.31 (0.18)
Wt of bight redfish, *Centroberyx gerrardi*	954.6	0.09 (0.04)	0.10 (0.05)
No. of bight redfish	681	0.06 (0.02)	0.08 (0.04)
Wt of ornate angelshark, *Squatina tergocellata*	951	0.08 (0.01)	0.10 (0.03)
No. of ornate angelshark	114	0.01 (0.00)	0.01 (0.00)
Wt of yellowspotted boarfish, *Paristiopterus gallipavo*	946.5	0.09 (0.03)	0.09 (0.02)
No. of yellowspotted boarfish	594	0.06 (0.02)	0.06 (0.02)
Wt of red gurnard, *Chelidonichthys kumu*	506.5	0.04 (0.01)	0.06 (0.02)
No. red gurnard	688	0.06 (0.02)	0.08 (0.03)
Wt of knifejaw, *Oplegnathus woodwardi*	253.4	0.02 (0.01)	0.03 (0.01)
No of knifejaw	289	0.03 (0.01)	0.03 (0.01)
Discarded catches			
Wt of total	39,439.8	3.25 (0.83)	4.72 (1.68)
Wt of wide stingaree, *Urolophus expansus*	29,118.0	2.12 (0.72)	3.84 (1.67)
No. of wide stingaree	47,484	3.43 (1.16)	6.22 (2.68)
Wt of jackass morwong, *Nemadactylus macropterus*	287.7	0.02 (0.01)	0.03 (0.01)
No. of jackass morwong	637	0.06 (0.02)	0.06 (0.02)
Wt of latchet, *Pterygotrigla polyommata*	5,960.7	0.64 (0.29)	0.53 (0.12)
No. of latchet	23,874	2.37 (0.97)	2.29 (0.52)

Random blocking effects for all models included 'pairs of deployments'. Weights (Wt) in kg. All variables were Ns at $p > 0.05$.

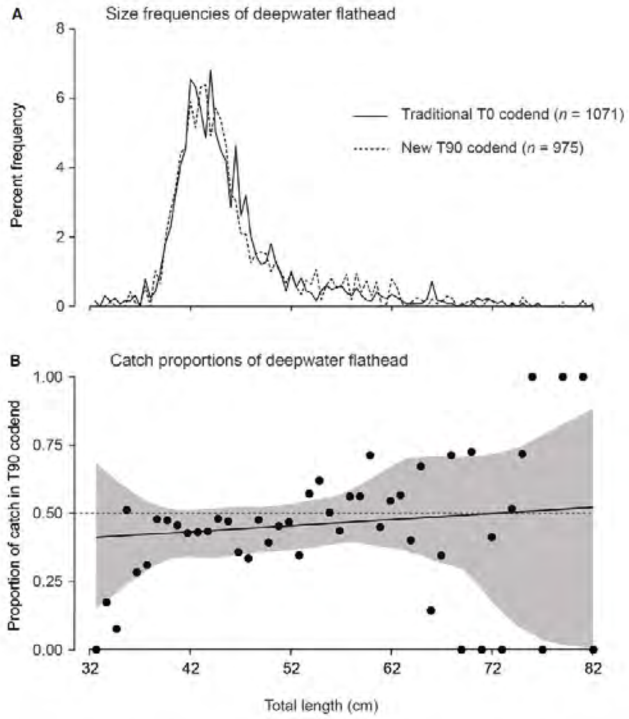

FIGURE 2
(A) Relative size-frequency plots for deepwater flathead, *Neoplatycephalus conatus*, retained in the traditional T0 and new T90 codends, and (B) plot of catch proportions with 95% confidence intervals designated by the shaded area and the horizontal dashed line marking 50% retention.

the T90 codend (predicted mean ± SE of 0.3 ± 0.01) than conspecifics in the T0 (0.2 ± 0.01). This result was due to slightly fewer cuts and a more natural belly colour (STable 1).

Discussion

The data here contribute toward ~20 primary literature studies since 1997 assessing T90 codends or part thereof (Kennelly and Broadhurst, 2021) and represent one of the few efforts outside European trawl fisheries (but see Lomelli et al., 2017; Cheng et al., 2020). However, contrary to general consensus, turning conventional meshes 90° in the anterior section (55%) of the codend here did not improve any species selection or size selection for deepwater flathead. Rather, significant effects were limited to a marginal improvement in fish quality. These outcomes can be discussed by considering the sizes of the abundant species and likely low selectivity of existing mesh—either as T0 or T90—but potentially improved movement of water through the latter meshes. Assuming validity of these suppositions, the data can then be used to suggest future modifications.

Previous studies assessing T90 throughout codends or only in anterior sections have shown increased sizes at 50% retention for various species (especially round fish including cod, *Gadus morhua*, haddock, *Melanogrammus aeglefinus*, and red mullet, *Mullus barbatus barbatus*), and often with maintained (e.g., Moderhak, 1997) or even reduced selection ranges (e.g., Wienbeck et al., 2011; Lomeli et al., 2017). Despite their name, like all platycephalids, deepwater flathead is not a 'flatfish', with congenerics having a maximum height-to-width ratio of ~0.5, which corresponds to the T90 shape (Broadhurst et al., 2006). Consequently, body shape is unlikely to have prevented small deepwater flathead from escaping. Instead, the relatively small mesh perimeter of ~187 mm clearly precluded egress of most sizes encountered, regardless of mesh orientation.

No published data are available on the morphometrics of deepwater flathead, but Broadhurst et al. (2006) showed that at maximum girths of 187 mm (mesh perimeter here), two platycephalids—the eastern blue spotted flathead, *P.*

caeruleopunctatus, and spikey flathead, *Ratabulus diversidens*—had TLs of 42.6 and 40.5 cm, respectively. These sizes are at the lower range of the deepwater flathead observed here. Potentially, if encountered, smaller deepwater flathead would escape through the T90 mesh.

Nevertheless, although not measured, several other species (especially discarded latchet, *Pterygortrigla polymnata*) were caught at sufficiently small sizes to pass through the mesh. These individuals should have had opportunity to escape, assuming the catch built up sufficiently, increasing the displacement of water forward and assisting some individuals to maintain position at the T90 cylinder (Broadhurst et al., 1999a). However, the double 4.1-mm Ø twine (thickness ~9% of the SMO) probably confounded selection (regardless of mesh orientation), considering the known negative implications of increasing twine diameter (e.g., Herrmann et al., 2013).

While there were no effects of T90 on relative size or species selection, the QIM data support the fishers' assertion of an improved physical quality of deepwater flathead (and better price). Other studies assessing similar codend changes (e.g., alternate materials or designs) to improve catch quality have shown comparable marginal (Brinkhof et al., 2021) or non-significant impacts (Tveit et al., 2019; Jensen et al., 2022). Much of the improved quality of deepwater flathead was attributed to fewer cuts/abrasions and possibly because the T90 cylinder allowed small debris to pass out of the codend, which would have been facilitated by the water displaced forward (Broadhurst et al., 1999a). Nevertheless, any explanation remains speculative and additional data are required to better quantify improvements in the landed-catch quality and temporal preservation implications due to the T90.

Conclusions

Unlike previous published studies assessing similar sizes or smaller T90 (to conventional T0) mesh in codends, we failed to show any selectivity improvements (Kennelly and Broadhurst, 2021). This anomaly might reflect research bias, where only positive effects are published, but it is also likely other gear parameters, including the small mesh size and double twine used, would have limited selection. Future research might benefit from assessing T90 in a slightly larger mesh size and/or a single twine in either the anterior section, or throughout the codend.

Beyond reducing unwanted catches of some small deepwater flathead when present, and other species, greater lateral mesh openings might further improve catch quality. However, because volume negatively affects catches through increased interactions, reducing unwanted catches of wide stingaree (~50% of the total catch) would be warranted. The small average weight (~0.6 kg) and sizes of the wide stingarees might preclude mechanical-separating grids. Anterior-trawl modifications, including changes to ground gears and/or dropout panels, might have greater utility, but will require consideration given that wide stingarees and deepwater flathead maintain similar positions on the substrate.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Ethics statement

The animal study was reviewed and approved by the NSW DPI Animal Care and Ethics Committee (ACEC REF 08-06).

Author contributions

Credit authorship: Conceptualization (MB, RM, and IK); Data curation (MB, IK); Formal analysis (RM); Funding acquisition (MB, IK); Investigation (MB, IK); Methodology (MB, RM, and IK); Project administration (MB); Resources (MB); Software (MB and RM); Supervision (MB); Validation (MB); Visualization (MB, RM, and IK); Roles/Writing – original draft (MB); Writing – review & editing (MB, RM, and IK). All authors contributed to the article and approved the submitted version.

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Conflict of interest

Author IK was employed by Fishwell Consulting.

The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fmars.2022.951549/full#supplementary-material

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Supplementary Tables

Supplementary Table 1. List of characters, scoring and means (SE) fish^{-1} assessing the external condition of replicate samples of deepwater flathead, *Neoplatycephalus conatus* caught in the traditional T0 and new T90 codends via the 'quality index method' (following Nielsen, 2005). Some measures are not entirely relevant but were included for completeness.

Character	Score	T0	T90
Skin sheen?	0, bright and shining; 1 bright, but not shining; and 2, dull	0.0 (0.0)	0.0 (0.0)
Bloodspots on gill cover?	0, none; 1, small (<3 mm diameter); or 2, large (> 3 mm diameter)	0.0 (0.0)	0.0 (0.0)
Stiffness?	0, stiff; 1, elastic; 2, firm; or 3, soft	1.0 (0.0)	1.0 (0.0)
Belly?	0, firm; 1, soft; or 2, ruptured	0.0 (0.0)	0.0 (0.0)
Scales?	0, 0% loss; 1, 25% loss; or 2, >50% loss	0.0 (0.0)	0.0 (0.0)
Fins?	0 no damage; 1, minor damage; or 2, extensive damage	0.0 (0.0)	0.0 (0.0)
Eye clarity?	0, clear; or 1, cloudy	0.0 (0.0)	0.0 (0.0)
Eye shape?	0, normal; 1, plain; or 2, sunken	0.0 (0.0)	0.0 (0.0)
Gill colour?	0, red; and 1, faded or discoloured	0.0 (0.0)	0.0 (0.0)
Belly colour?	0, natural colour, or 1, yellow patches	0.2 (0.0)	0.1 (0.0)
Cuts or trauma to the body?	0, none; 1, 1 or 2 cuts; 2, 3 or 4 cuts; or 3 >4 cuts	0.2 (0.0)	0.1 (0.0)

Supplementary Table 2. List of species (common and Latin names) caught in descending weights, and their numbers and % weight discarded during 24 deployments of the traditional T0 and new T90 codends in the Great Australian Bight during December, 2021.

Species	Wt (kg)	No.	% discarded (wt)
Wide stingaree, *Urolophus expansus*	29178.0	47555	99.8
Latchet, *Pterygotrigla polyommata*	9174.6	36216	64.9
Deepwater flathead, *Neoplatycephalus conatus*	6910.0	9006	0
Gummy shark, *Mustelus antarcticus*	2000.9	695	0.3
Ocean jacket, *Nelusetta ayraudi*	1764.5	3382	7.9
Bight redfish, *Centroberyx gerrardi*	1498.2	681	0
Ornate angelshark, *Squatina tergocellata*	1048.5	181	9.3
Yellowspotted boarfish, *Paristiopterus gallipavo*	948.0	597	0.2
Sponge, Porifera	762.0	7	100
Swallowtail, *Centroberyx lineatus*	707.7	3120	100
Red gurnard, *Chelidonichthys kumu*	511.5	704	1.0
Knifejaw, *Oplegnathus woodwardi*	348.6	480	27.3
Jackass morwong, *Nemadactylus macropterus*	315.6	666	91
Jack mackerel, *Trachurus declivis*	310.9	3094	100
Southern fiddler ray, *Trygonorrhina dumerilii*	304.0	89	100
Blue morwong, *Nemadactylus valenciennesi*	227.9	59	0
Gould’s squid, *Nototodarus gouldi*	224.4	330	18.6
Miscellaneous benthos	206	Na	100
Common gurnard perch, *Neosebastes scorpaenoides*	166.1	405	100
Deepwater stargazer, *Kathetostoma nigrofasciatum*	159.9	500	100
Southern eagle ray, *Myliobatis tenuicaudatus*	158.0	34	0
Smooth stingray, *Dasyatis brevicaudata*	145.5	16	100
Whitebarred boxfish, *Anoplocapros lenticularis*	138.6	177	100
Australian burrfish, *Allomycterus pilatus*	125.7	244	100
Blackspotted gurnard perch, *Neosebastes nigropunctatus*	109.2	145	0
Ringed toadfish, *Omegophora armilla*	109.2	466	100
John dory, *Zeus faber*	103.0	67	0
Mosaic leatherjacket, *Eubalichthys mosaicus*	98.6	104	100
Tusk, *Dannevigia tusca*	83.0	62	0
Spotted wobbegong, *Orectolobus maculatus*	77.0	2	0
Port Jackson shark, *Heterodontus portusjacksoni*	76.6	40	100
Blackspot boarfish, *Zanclistius elevatus*	47.5	100	0
Rusty carpetshark, *Parascyllium ferrugineum*	45.1	49	100
Greeneye dogfish, *Squalus* spp.	40.0	18	100
Melbourne skate, *Spiniraja whitleyi*	38.0	3	100
Yelloweye redfish, *Centroberyx australis*	35.1	46	100
Conger eel, Congridae	34.0	10	0
Samsonfish, *Seriola hippos*	34.0	1	0
Common sawshark, *Pristiophorus cirratus*	28.0	14	63.6
Red cod, *Pseudophycis bachus*	26.6	70	100
Western shovelnose ray, *Aptychotrema vincentiana*	23.4	18	100
Cuttlefish, Sepiidae	22.7	78	100
School shark, *Galeorhinus galeus*	21.5	3	0
Gemfish, *Rexea solandri*	21.0	42	100
Spikey dogfish, *Squalus megalops*	19.0	17	100
Sergeant baker, *Latropiscis purpurissatus*	15.2	14	100
Whiskery shark, *Furgaleus macki*	15.0	2	0
Triggerfish, Balistidae and leatherjacket, Monacanthidae	14.0	12	0
Hard coral, undifferentiated	12.3	0	100
Footballer sweep, *Neatypus obliquus*	11.4	14	100
Bighead gurnard perch, *Neosebastes pandus*	10.9	27	100
Common veilfin, *Metavelifer multiradiatus*	10.0	29	100
Thetis fish, *Neosebastes thetidis*	10.0	20	100
Broadnose shark, *Notorynchus cepedianus*	8.0	1	0
Silver trevally, *Pseudocaranx georgianus*	4.9	12	22.4
Southern calamari, *Sepioteuthis australis*	4.9	5	0
Bigeye ocean perch, *Helicolenus barathri*	3	20	100
Cosmopolitan rubyfish, *Plagiogeneion rubiginosum*	3	30	100
Sandpaper fish, *Paratrachichthys macleayi*	3	16	100
Southern rock lobster, *Jasus edwardsii*	3	4	100
Elephantfish, *Callorhinchus milii*	1.8	1	0
Blue mackerel, *Scomber australasicus*	1.6	3	100
Spiny boxfish, *Capropygia unistriata*	1.3	5	100
Crab, Brachyura	1	10	100
Fourspine leatherjacket, *Eubalichthys quadrispinis*	0.8	1	100
Velvet leatherjacket, *Meuschenia scaber*	0.6	3	100
Cocky gurnard, *Lepidotrigla modesta*	0.3	14	100

Appendix 8. Broadhurst, M.K., Knuckey, I.A. and Millar, R.B. 2023. Using a horizontal-separator panel in an Australian fish trawl to quantify species-specific changes in vertical orientations during capture. Fish. Res. 261, 106618. doi: 10.1016/j.fishres.2023.106618

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Using a horizontal-separator panel in an Australian fish trawl to quantify species-specific changes in vertical orientations during capture

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Selectivity

ABSTRACT

Owing to few data describing species-specific vertical orientations during capture in Australian fish trawls, but the need for information to progress modifications to improve selectivity and reduce operational costs, a generic trawl was fished with upper and lower ('dual') extensions/codends, and with and without a horizontal-separator panel in the posterior 50% of the body. The two configurations facilitated quantifying the vertical orientations of species from the mid to posterior trawl body based on catches. During 32 deployments, 13 and eight commercial and non-commercial species/groups were caught in sufficient quantities for analyses. The commercial species entered the posterior trawl at varying heights, but many individuals (including the most abundant, tiger flathead, *Platycephalus richardsoni* and especially larger fish) initially orientated low in the mid trawl, and then moved upwards at the posterior trawl to present similar catches in each of the dual codends. Eastern school whiting, *Sillago flindersi* was the only commercial species showing the opposite behaviour, entering higher in the mid trawl before orientating downwards. Non-commercial catches were biased towards rays, skates and stingarees (46%) and all except smooth stingrays, *Bathytoshia brevicaudata* mostly entered the lower posterior trawl, with proportionally fewer than commercial species eventually rising upwards. The data benefit prioritizing future modifications for regional testing, including lowering the headline and increasing mesh size in the anterior, upper trawl body to reduce drag (which might not greatly affect catches of commercial species) and/or changing the lower anterior trawl body to stimulate key fish to rise up earlier, and potentially facilitate separating unwanted elasmobranchs, possibly via bottom-opening grids or larger meshes/drop-out panels in the posterior trawl. More broadly, the data reiterate the benefits of horizontal-separator panels for providing insight into species-specific behaviour in trawls, supporting their application in other fisheries.

1. Introduction

Demersal fish trawling is among the world's most common fishing methods, accounting for ~25% of the total ocean harvest (estimated at ~98 m t; Pauly et al., 2020) and supporting the fishing economies of most coastal countries (Kennelly and Broadhurst, 2021). However, owing to poor selectivity, fish trawling also accounts for ~30% of global discards (Pérez Roda et al., 2019)—the mortalities of which have raised environmental concerns and evoked historical and ongoing efforts at improving selectivity (Madsen, 2007; Kennelly and Broadhurst, 2021).

Recently, Kennelly and Broadhurst (2021) identified > 70% of efforts to improve fish-trawl selection have focused on changing the extension or codend (i.e. the aft section of the trawl). Typically, these changes involve optimizing lateral-mesh openings to match the morphology of key species via simple increases in conventional diamond-shaped meshes ('T0' mesh) or alternative shapes such as T90 and T45 (either throughout the codend or at strategic locations). In some cases, more complex grids have been used to separate catches in codends (Kennelly and Broadhurst, 2021). Despite recognised benefits for concomitantly reducing drag (and therefore fuel consumption), less attention has been directed towards manipulating the anterior sections of fish trawls, including the body, to improve selection. Such bias in

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efforts is at least partly attributed to a need for some understanding of species-specific behavioural responses to trawls—information that is lacking for most species other than key targets in North Atlantic fisheries (e.g. Atlantic cod, *Gadus morhua* and haddock, *Melanogrammus aeglefinus*; Winger et al., 2010; Pol and Eayrs, 2021).

A paucity of data describing the behaviour of a plethora of target and bycatch species in trawls has limited attempts at assessing anterior trawl modifications in many fisheries (beyond those in Europe and North America), including Australia (Kennelly and Broadhurst, 2021). Currently there are 14 separately managed Australian fish-trawl fisheries comprising 135 fishing licences; but by far the greatest effort (>65%) occurs along the continental shelf from Sydney, New South Wales (NSW) south around Tasmania and west to Cape Jervis, South Australia, and is mostly managed as the 'commonwealth trawl sector' (CTS). Trawlers in the CTS tow single-rigged trawls (~30–45 m headline lengths with a minimum stretched mesh opening–SMO of 90 mm in the codend) to target ~20 species, among which tiger flathead, *Platycephalus richarsoni* is often dominant, but they retain > 100 other species listed as commercially important 'by-product'. Vessels also generally have high levels of incidental non-commercial catches (or 'bycatch') which can comprise > 280 species and 40–60% by weight of the total catches. Concerns over the unwanted fishing mortality of bycatches (especially elasmobranchs; Graham et al., 2001) and juveniles of over-exploited target species, have precipitated recent attempts at more selective fishing (Hunt et al., 2014; Broadhurst and Millar, 2022).

The diversity of target and non-target species, their different sizes and shapes, and often similar depth distributions presents a challenge for identifying selective modifications beyond matching the SMO in the codend to the smallest targets. Further, while most species are assumed to be predominantly benthic, very little work has been done to investigate species-specific behaviours in trawls used in the CTS or any Australian fishery (Piasente et al., 2004; Yanase et al., 2009). Such information can assist with designing modifications to improve trawl selectivities/efficiencies.

Visual observations of fish reactions to trawls using cameras are probably the best approach for acquiring the required data (e.g. Piasente et al., 2004), although logistically these can be difficult to use, especially because their light sources can confound fish behaviour (Marchesan et al., 2005; Pol and Eayrs, 2021). Other digital options include dual frequency identification sonar (DIDSON), although specialist equipment is required, and differentiating multiple species and/or sizes can be challenging (Rakowitz et al., 2012). Perhaps the simplest option to inform broad species-specific orientations in trawls (e.g. where they enter or position in the trawl and therefore might be promoted to escape) is to use separator panels (Cotter et al., 1997; Engås et al., 1998; Ferro et al., 2007; He et al., 2008; Holst et al., 2009).

Specifically, a horizontal panel positioned in the trawl body and leading to lower and upper codends ('dual codends') can separate downwards- from upwards-rising species, with possibilities for better selectivity via anterior and/or posterior trawl-body modifications (Cotter et al., 1997; Engås et al., 1998; Ferro et al., 2007; Holst et al., 2009). Assessing only dual codends might also have utility in determining behaviours once species have been herded to the posterior trawl prior to capture (Krag et al., 2009). Both types of separators could facilitate obtaining information to design other compartment-specific modifications to trawls (Holst et al., 2009).

Considering the above, the aim in this work was to install a horizontal-separator panel and dual codends in a typical CTS trawl, and first investigate any species- or size-specific trends by key species at the mid trawl body. We then removed the horizontal-separator panel, but left the dual codends to determine the responses of key species once they had been herded into the posterior trawl body. Last, we sought to use the acquired species-specific information to propose future modifications to regional trawls that might be used to improve their selection.

2. Methods

This study was done off the southern NSW coast (35.46° S; 150.56° E to 36.56° S; 150.15° E) on established trawl grounds (53–420 m) between 27 April and 23 May 2022 using a 23 m trawler with a 588 Kw engine (FV 'Francesca'). The vessel was rigged with a single, conventional anterior trawl body (42-m headline length and made entirely of knotted polyethylene–PE twine) attached to 24-m bridles, 274-m sweeps (20-mm diameter–Ø rope) and 600 kg steel V otter boards (Figs. 1 and 2). On-board equipment included a Notus trawl-monitoring system to measure otter-board spread and headline height (m) at the trawl, and a Lowrance global positioning system (GPS) to record the distance travelled and speed over the ground (SOG).

2.1. Dual codends and horizontal-separator panel

The posterior trawl was modified to include two separator configurations for each experiment. For both experiments, the conventional trawl extension (measuring 100 meshes in the normal direction–N and 120 meshes in the transverse direction–T) and codend (33 N × 120 T) were removed, and replaced with a flexible circular wire-rope frame (2.5-m Ø horizontal cross section) made from 25-mm Ø stainless-steel wire to facilitate attaching two identical (upper and lower) extensions and codends (Fig. 2). The new extensions were made from conventional nominal 104-mm SMO PE netting (3.5-mm Ø twine) and measured 100 N × 80 T (Fig. 2). Each extension was sewn to a codend made from nominal 93-mm SMO PE netting (7.2-mm Ø twine) (Fig. 2). The codends had different-coloured lifting rings sewn 20 N anterior to the drawstrings to facilitate their identification during retrieval onboard.

A removable panel (219 T × 156 N) made from neutral-knotted (i.e. with no lift force; Broadhurst et al., 2016) nominal 87-mm SMO PE netting (1.8-mm Ø twine) was designed as a horizontal separator to compartmentalise the posterior 50% of the trawl body, and at the vertical midline (Figs. 1 and 2). The size of the separator panel was calculated following the assumed geometry of the conventional trawl in terms of wing-end spread (~52%) at the fished depths, along with the number of meshes in circumference and their maximum opening of 35–40%. The panel was secured (hanging ratio of ~30%) at its leading edge to 6.5 m of 4-mm Ø Dynemea®, and along its sides (2N2B taper) to braided PE rope (16 mm Ø) and laced into the posterior ~50% of the trawl body starting where the conventional top and bottom panels tapered into identical 92.5-mm SMO mesh (Fig. 1). The aft end of the separator panel was evenly sewn along the horizontal cross section in the wire-rope frame separating the dual codends (Fig. 2).

During the first five days at sea (experiment 1), both the horizontal-separator panel and dual codends were secured to the trawl, and it was repeatedly deployed for 1.4–3.1 h between 04:35 and 14:45 h. The horizontal-separator panel was then removed and the trawl was fished with only the dual codends between 04:00 and 16:00 for 1.4–3.5 h over the next five days (experiment 2).

2.2. Sampling protocol and data collected

Prior to fishing, all sections of the trawl, horizontal-separator panel, extensions and codends were measured for replicate (n = 20) SMOs using a purpose-built gauge (Fig. 1). The assumption of no difference in SMOs between the dual extensions and codends was then tested using a linear model (LM).

The sampling and data collection remained the same for both trawl configurations. During fishing, technical data collected included the: trawled location; distance (km) and duration (h; warp winch brakes on and off); otter-board spread (m); headline height (m); SOG (ms^{-1}); and depth (m) of the trawl. The latter three variables were logged every ~15 min to provide an average for each deployment.

After retrieval, the dual codends were emptied into separate holding areas (with measured volumes), and their total catch weights were

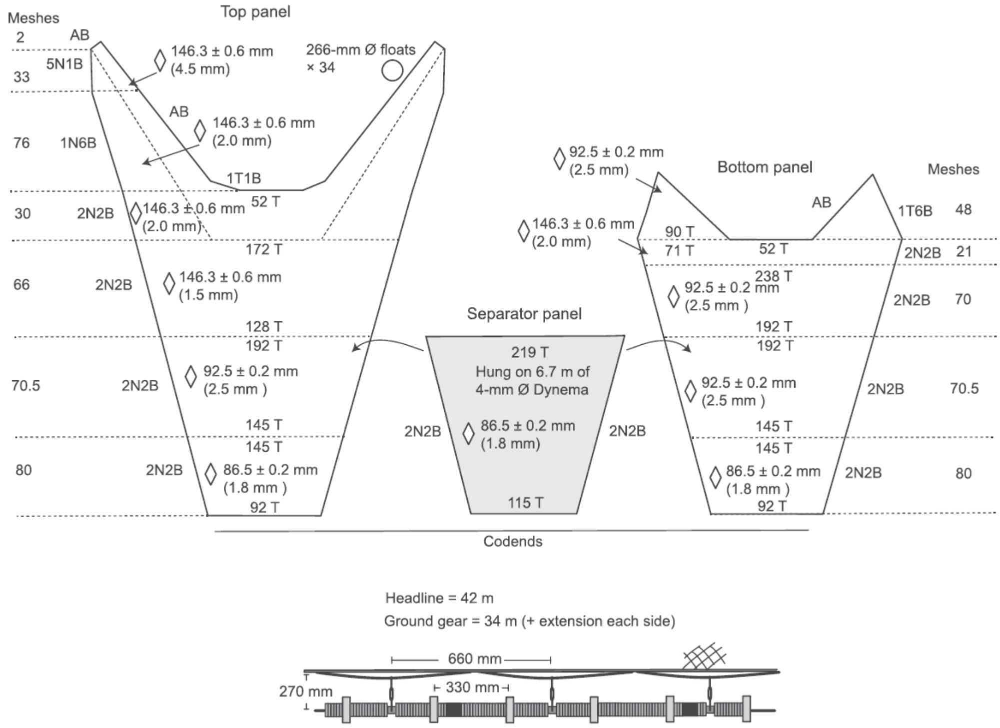

Fig. 1. Plan of the trawl fished during the experiments with location of the horizontal-separator panel in the posterior body. Ø, diameter; N, normal direction; T, transverse direction; mesh size is stretched mesh opening; twine Ø in parentheses.

estimated. Retained catches were separated by species and placed into boxes before being weighed, counted and most measured to the nearest 0.5 cm total length (TL). The total weights of discarded catches (bycatch) from each codend were either also placed into boxes and weighed or, where there were excessive amounts, estimated by subtracting the retained component from the total catch. Either all, or a subsample, of the discarded catches was individually identified to species, counted and weighed in the subsample and extrapolated to the total. Randomly selected subsamples of key species (up to 150 deployment^{-1}) were measured to the nearest 0.5 cm total length (TL).

2.3. Data analyses

The SMOs of the paired extensions and codends were analysed using linear models (LM). Data describing otter-board spread and headline height were analysed across experiments using linear mixed models (LMM) that included the fixed effects of 'trawl configuration' (separator panel in experiment 1 and dual codends only in experiment 2), and the co-variates 'depth' and 'SOG'. 'Days' was included as a random term. A backward-selection algorithm was employed with non-significant fixed terms removed until the remaining terms were significant.

Catch weights were analysed using mixed models with fixed effects including 'experiment' (i.e., the trawl configured with or without the horizontal-separator panel), 'codends' (upper or lower) and 'depth'. However, of primary interest was the interaction term between experiment and codends, which represented the effect of the horizontal-separator panel (i.e. its presence or absence) on any differences in catches between the upper and lower codends, and therefore compartmentalized fish distributions as they moved through the mid to posterior trawl. Random effects in all models included 'days' and 'deployments'.

Initially, a LMM was applied to the response variable log(catch+1), but for many catch variables there were high proportions of zeroes and the underlying assumption of approximate normality was violated. Instead, the Tweedie distribution (which innately incorporates zero inflation in non-negative numeric data and is fitted on the log scale) was assumed for the catch weights fitted using a generalized linear mixed model (GLMM). The Tweedie GLMM was fitted using the glmmTMB function from the R package of the same name. The statistical significance of fixed effects was evaluated at the 5% level using Wald tests.

Where there were sufficient size data for individual species, any effects of TL on the probabilities of a fish entering the upper codend were assessed using size-selectivity analyses (Millar, 1992; Wileman et al., 1996). The approach followed standard procedures used for relative selectivity analysis of two fishing gears (e.g. Broadhurst et al., 2018). Specifically, for each TL class the proportion of the total catch caught in the upper codend was modelled using logistic regression. More flexible spline and polynomial curves were also trialled but found to be too unstable. Prior to analyses, catch frequencies were first scaled to take in to account any subsampling. Bootstrapping (Millar, 1993, 2011) was used to account for between-haul variation (Millar et al., 2004) and to determine valid p-values for the statistical significance of the TL effect on relative selectivity. All analyses were done in R (Anon, 2021) and the selectivity analyses made use of the SELECT package (Millar, 2021).

3. Results

There was minimal variability within mean SMOs for the various trawl sections (Fig. 1). There were no significant differences in SMOs between extensions (pooled mean ± SE of 103.5 ± 0.2 mm) or codends (92.8 ± 0.4 mm) (LM, $p > 0.05$). In total, 17 and 15 deployments were competed assessing the horizontal-separator panel (experiment 1) and dual codends only (experiment 2), and across comparable depths (136.2 ± 20.0 and 107.5 ± 0.9 m), deployment durations (identical means and SE at 2.5 ± 0.1 h) and SOGs (1.6 ± 0.0 and 1.7 ± 0.0 ms^{-1}). There were

Table 1
Summaries of the fixed effects examined using Tweedie generalized linear mixed models to explain variation among the weights of total, commercial and non-commercial species caught during experiments 1 (horizontal-separator panel; HSP with dual codends) and 2 (dual codends only) with multiplicative effects (± SE) listed for the categorical factors of 'experiment' (relative to experiment 1 or presence of HSP), 'codends' (relative to lower codend, irrespective of HSP) and their interaction (upper codend in experiment 2, relative to that in experiment 1).

Variable	Experiment (E: HSP present vs absent)	Codends (C: upper vs lower)	E × C	Depth
Total catch	1.21 (0.22) ns	0.31 (0.03)***	2.51 (0.40)***	***
Commercial species				
Total commercial catch	1.46 (0.29) ns	0.46 (0.05)***	2.63 (0.43)***	ns
Tiger flathead, *Platycephalus richardsoni*	1.06 (0.26) ns	0.31 (0.06)***	3.92 (1.07)***	ns
Silver trevally, *Pseudocaranx georgianus*	3.42 (3.47) ns	0.70 (0.20) ns	3.21 (1.06)***	ns
Southern sawshark, *Pristiophorus nudipinnis*	4.73 (1.93)***	0.02 (0.02)***	9.79 (10.59)*	ns
Red gurnard, *Chelidonichthys kumu*	2.99 (1.05)**	0.91 (0.20) ns	1.52 (0.40) ns	ns
Eastern angelshark, *Squatina albipunctata*	0.41 (0.15)*	0.13 (0.06)***	11.67 (6.55)***	*
Blue mackerel, *Scomber australasicus*	1.24 (1.47) ns	0.54 (0.24) ns	4.65 (2.56)**	*
Yellowtail scad, *Trachurus novaezelandiae*	2.32 (1.62) ns	3.59 (1.72)**	0.47 (0.28) ns	**
Gould's squid, *Nototodarus gouldi*	0.45 (0.18)*	1.45 (0.22)*	2.90 (0.85)***	*
John dory, *Zeus faber*	0.97 (0.36) ns	0.60 (0.19) ns	13.81 (5.37)***	*
Grey morwong, *Nemadactylus douglasii*	1.31 (0.75) ns	0.06 (0.03)***	2.95 (1.81) ns	ns
Longfin bigeye, *Cookeolus japonicus*	3.12 (3.02) ns	6.780 (5.03)**	0.82 (0.67) ns	ns
Eastern school whiting, *Sillago flindersi*	1.80 (1.24) ns	0.70 (0.42) ns	0.16 (0.14)*	ns
Redfish, *Centroberyx affinis*	3.01 (2.56) ns	0.18 (0.13)*	4.23 (3.52) ns	ns
Non-commercial species				
Total non-commercial catch	1.16 (0.28) ns	0.21 (0.04)***	2.20 (0.61)**	***
Blacktip cucumberfish, *Paraulopus nigripinnis*	0.14 (0.08)***	0.33 (0.06)***	3.17 (1.20)**	***
Eastern fiddler ray, *Trygonorrhina fasciata*	1.88 (1.23) ns	0.09 (0.06)***	0.78 (0.62) ns	ns
Miscellaneous batoids	0.72 (0.18) ns	0.02 (0.01)***	16.71 (10.60)***	*
Smooth stingray, *Bathytoshia brevicaudata*	1.01 (0.71) ns	0.77 (0.69) ns	1.85 (1.85) ns	ns
Velvet leatherjacket, *Meuschenia scaber*	0.62 (0.40) ns	0.50 (0.12)**	9.20 (2.84)***	ns
Australian burrfish, *Allomycterus pilatus*	1.05 (0.35) ns	0.36 (0.11)***	3.99 (1.44)***	ns
Gurnards, *Lepidotrigla mulhalli* and *L. modesta*	0.26 (0.09)***	0.18 (0.05)***	3.65 (1.36)***	ns
Barracouta, *Thyrsites atun*	0.64 (0.34) ns	2.10 (0.77)*	0.65 (32) ns	ns

* $p < 0.05$;
** $p < 0.01$;
*** $p < 0.001$; ns, not significant

and 4).

3.2. Non-commercial species orientations

Among the eight non-commercial species/groups, the most abundant individuals were black cucumberfish, *Paraulopus nigripinnis* (24%), although > 45% of non-commercial catch comprised > 15 species of rays, skates and stingarees (Supplementary Table 1). As for commercial species, there were significant depth, experiment and codend effects among most variables (GLMM, $p < 0.05$, Table 1, Fig. 5). Five species/groups, including blacktip cucumberfish, miscellaneous batoids, velvet leatherjacket, *Meuschenia scaber*, Australian burrfish, *Allomycterus pilatus* and gurnards, *Lepidotrigla mulhalli* and *L. modesta* returned a significant experiment × codend interaction, contributing towards the same for the total non-commercial catch (GLMM, $p < 0.01$; Table 1, Fig. 5a, b, d and f–h). Most individuals of these species remained low at the mid-point of the trawl, passing under the horizontal-separator panel during experiment 1 and then, during its absence in experiment 2, many rose upwards in the posterior body to be either (1) slightly (miscellaneous batoids) or (2) considerably (velvet leatherjacket) more abundant in the upper codend, or (3) more evenly distributed between both codends (blacktip cucumberfish, Australian burrfish, and gurnards) (Figs. 4 and 5a, b, d and f–h).

For the remaining analysed species, eastern fiddler ray, *Trygonorrhina fasciata* and barracouta, *Thyrsites atun* returned significant main effects of codends—consistently orientating and remaining towards the lower and upper posterior trawl body, respectively (GLMM, $p < 0.05$; Table 1, Figs. 4 and 5c and i). Smooth stingray, *Bathytoshia brevicaudata* was the only species not significantly affected by the trawl separation, with no clear preference towards either upper or lower sections (GLMM, $p > 0.05$; Table 1, Figs. 4 and 5e).

3.3. Length-dependent orientations

The relative size-selectivity analyses were restricted to species present in at least six deployments in both experiments, or 12 deployments in one experiment. These thresholds limited analyses to the commercially important tiger flathead, red gurnard and john dory, and the non-commercial blacktip cucumberfish, velvet leatherjacket and (grouped) gurnards. Significant TL-dependent effects of codends were limited to tiger flathead ($p < 0.05$) in experiment 1, but not experiment 2 ($p > 0.05$) and john dory ($p < 0.01$) over both experiments (Fig. 6). These effects manifested as greater proportions of larger tiger flathead in the lower posterior trawl in the presence of the horizontal-separator panel in experiment 1, but no differences among sizes with only the dual codends in experiment 2 (Fig. 6a and b). For john dory, there was an overall positive relationship between TL and orientation in the upper posterior trawl (Fig. 6c).

4. Discussion

This study represents the first quantitative assessment of species- and size-specific vertical orientations in Australian fish trawls, and complements the few regional qualitative studies (Piasente et al., 2004; Yanase et al., 2009). Like for previous work done overseas, the data demonstrate considerable inter- and some intra-specific differences among vertical orientations during movement through the posterior trawl; many of which remain cryptic while some might be explained by general morphology and/or size (Engås et al., 1998; Ferro et al., 2007; Holst et al., 2009). The observed differences among species might be used to prioritise modifications to improve the environmental performance of regional trawls, but first some discussion of the experimental design, trawl geometry and any possible confounding effects of the horizontal-separator panel and/or dual codends warrant consideration.

While a conventional trawl (with a single codend) was not fished here, the otter-board spreads and headline heights were within the

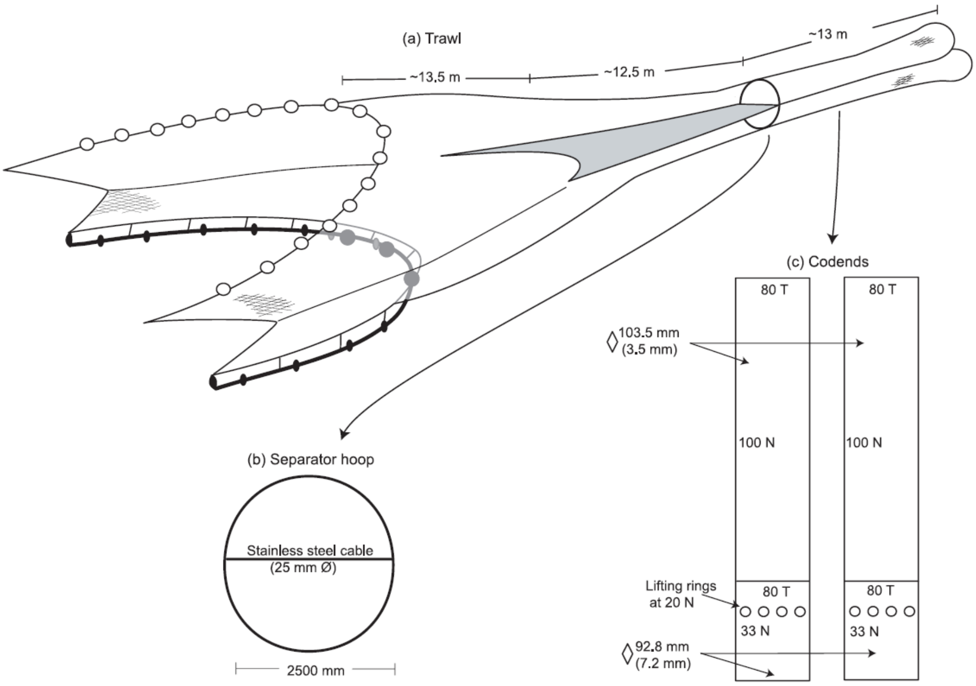

Fig. 2. Schematic diagrams of the (a) trawl with the horizontal-separator panel installed, (b) separator hoop at the posterior body, and (c) dual codends fished during the experiments. Ø, diameter; N, normal direction; T, transverse direction; mesh size is stretched mesh opening (and also lengths are based on stretched meshes); twine Ø in parentheses.

no significant differences between otter-board spreads or headline heights of the trawl when rigged with the horizontal-separator panel in experiment 1 (113.6 ± 6.6 and 4.0 ± 0.4 m) or dual codends only during experiment 2 (121.4 ± 6.7 and 4.4 ± 0.3 m) (LMM, $p > 0.05$). Regardless of trawl configuration, the depth of water significantly and positively affected otter-board spread (LMM, $p < 0.01$), but there were neither concomitant effects on headline height, nor did SOG affect either variable (LMM, $p > 0.05$).

There were no operational issues with either the horizontal-separator panel or the dual codends. Very few fish were observed impinged in meshes in either the horizontal-separator panel or posterior body, with catches accumulating in the dual codends typical of conventional fishing. In total, 19.8 t was caught, of which 7.7 t comprised > 46 commercial species and 12.1 t included > 33 non-commercial species (Supplementary Table 1). Beyond total catches, individual catch analyses were restricted to 12 and eight commercial and non-commercial species/groups, comprising 85% and 78% of the respective catches (Supplementary Table 1).

3.1. Commercial species orientations

Tiger flathead was the most abundant commercial species by weight (24% of that component of catches), followed by silver trevally, *Pseudocaranx georgianus* (12%), southern sawshark, *Pristiophorus nudipinnis* (10%), red gurnard, *Chelidonichthys kumu* (10%), and eastern angleshark, *Squatina albipunctata* (9%) (Supplementary Table 1). The remaining eight species each comprised ≤ 5% of commercial catch (Supplementary Table 1).

The GLMM returned significant main effects of either depth (reflecting species-specific habitat preferences), experiment or codends on the total catch, and catches of most commercial species ($p < 0.05$); however for nine commercial species/groups (of 13 analysed), the two technical factors of interest were confounded by significant interactions (GLMM, $p < 0.05$; Table 1, Fig. 3). Plots of the interaction mean (+SE) catches in the dual codends showed that with the horizontal-separator panel installed (experiment 1), there was a clear trend towards entering the lower trawl among tiger flathead, silver trevally, *Pseudocaranx georgianus*, southern sawshark, *Pristiophorus nudimpinnis*, eastern angel shark, *Squatina albipunctata*, blue mackerel, *Scomber australasicus*, and john dory, *Zeus faber* contributing towards a relatively greater weight of total commercial species (and total catch overall) (Fig. 3a–d, f, g and j). But when the horizontal-separator panel was removed (experiment 2), these species all had greater relative catches in the upper codend (that were considerable for all except southern sawshark) (Table 1, Fig. 3a–d, f, g and j). The relative differences indicate many individuals of these species mostly remained low at the midpoint of the trawl body, but then rose upwards at the posterior section before the extension (Fig. 4).

Significant interactions between experiment and codends were also detected for the less abundant Gould's squid, *Nototodarus gouldi* and eastern school whiting, *Sillago flindersi* (GLMM $p < 0.05$) However, both species entered the mid trawl slightly biased towards the upper compartment and then, in the absence of the horizontal-separator panel, at the posterior trawl proportionally more Gould's squid moved upwards, while eastern school whiting moved downwards (Figs. 3i and m and 4). There were no other interactions between experiment and codends, but there were significant main effects of the latter for yellowtail scad, *Trachurus novaezelandiae*, grey morwong, *Nemadactylus douglasii*, longfin bigeye, *Cookeolus japonicus* and redfish, *Centroberyx affinis* (GLMM, $p < 0.05$; Table 1, Fig. 3h, k, l and n). Individuals of yellowtail scad and longfin bigeye trended towards entering and remaining in the upper posterior trawl, while many grey morwong and, to a lesser extent, redfish entered and remained low (Fig. 3 h, k, l and n and 4). The only species not significantly affected by codends was red gurnard, implying no vertical preference in the posterior trawl with or without the horizontal-separator panel (LMM, $p > 0.05$; Table 1, Figs. 3e

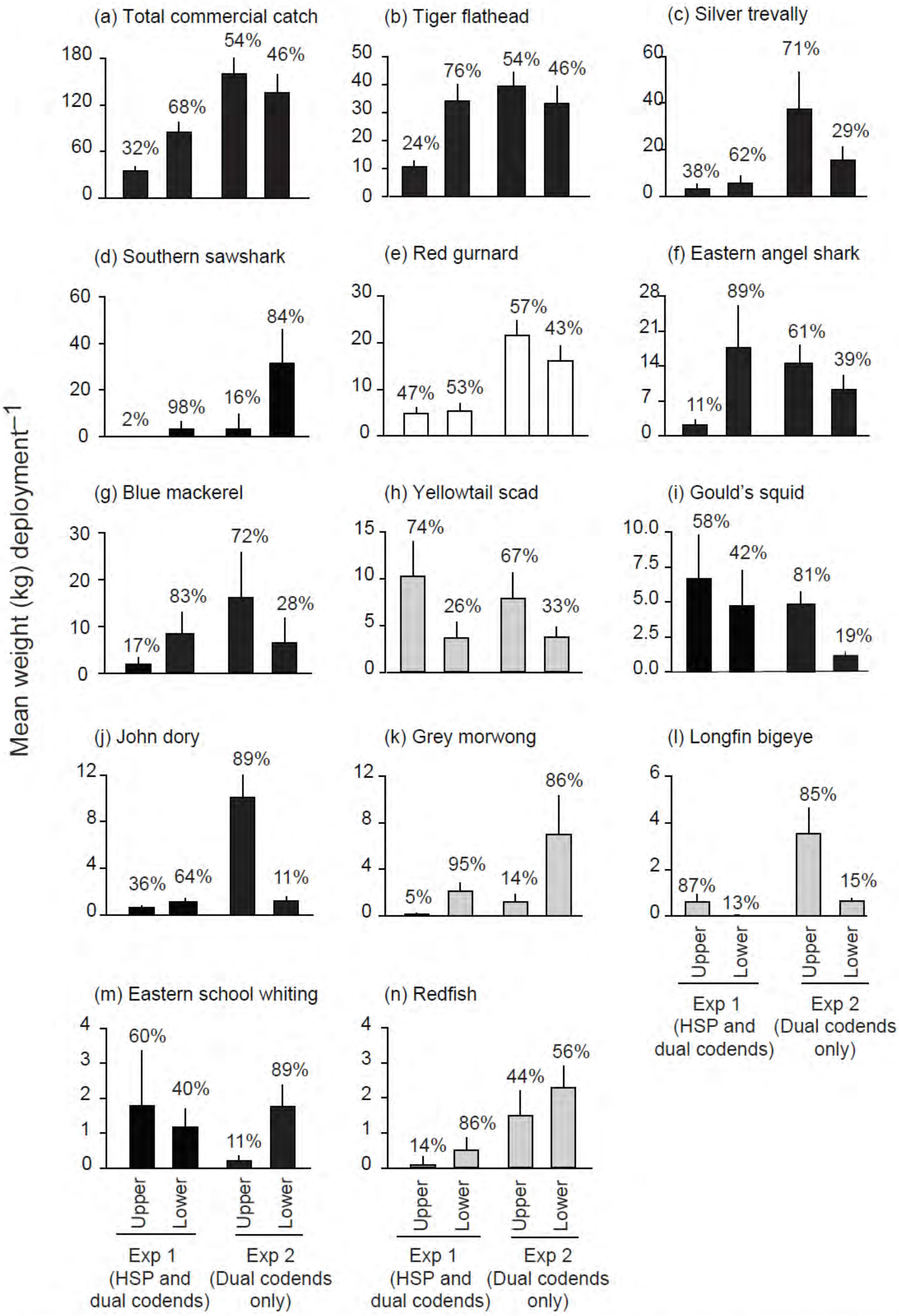

Fig. 3. Commercial groups/species (in order of abundance): mean (+SE) weights deployment^{-1} separated by experiment and codend of (a) total catch, (b) tiger flathead, *Platycephalus richardsoni*, (c) silver trevally, *Pseudocaranx georgianus*, (d) southern sawshark, *Pristiophorus nudipinnis* (e) red gurnard, *Chelidonichthys kumu*, (f) eastern angel shark, *Squatina albipunctata*, (g) blue mackerel, *Scomber australasicus*, (h) yellowtail scad, *Trachurus novaezelandiae*, (i) Gould's squid, *Nototodarus gouldi*, (j) john dory, *Zeus faber*, (k) grey morwong, *Nemadactylus douglasii*, (l) longfin bigeye, *Cookeolus japonicus*, (m) eastern school whiting, *Sillago flindersi* and (n) redfish, *Centroberyx affins*. All black, grey or white histograms indicate a significant interaction (experiment × codend), main effect of codends or no significant gear effects, respectively (Tweedie generalized linear mixed models, $p < 0.05$), while the % are contributions to total catch in each experiment.

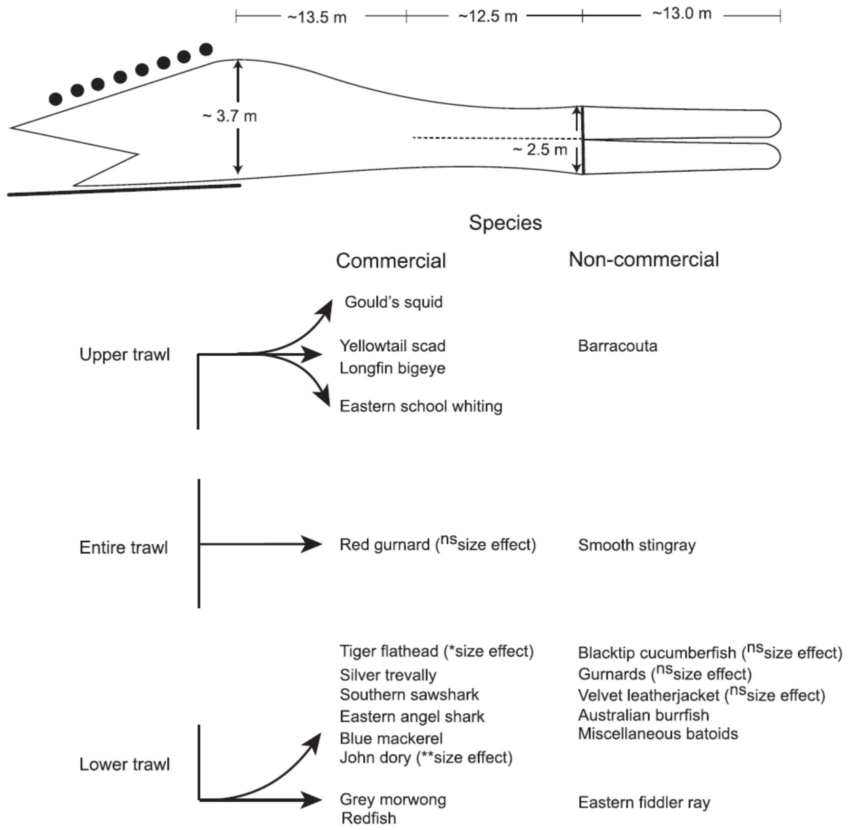

Fig. 4. Side view of the trawl, with the average headline height and approximate stretched lengths (m) of sections and the general bias towards upper or lower (or neither) separated compartments for key species based on the histograms in Figs. 3 and 5. Species assessed for relative size-frequency analyses are marked, with the significance or otherwise (ns) of outcomes.

reported ranges for similar trawls fished conventionally (Broadhurst and Millar, 2022). The lack of any significant effects on these two parameters associated with the presence or absence of the horizontal-separator panel, but a clear overall effect of depth on otter-board spread, supports few confounding effects. More specifically, the positive effect of depth on otter-board spread is consistent with previous studies on trawl geometry and can be explained by a reducing divergence angle of the warp along with inward forces (Weinberg and Kotwicki, 2008). A concomitant effect on headline height was not evident, but this could reflect the sweep and bridle lengths (~300 m) and/or the buoyed headrope, minimizing any detectable changes.

The lack of detectable effects on trawl-mouth geometry due to the horizontal-separator panel might be expected considering it was restricted to the posterior 50% of the trawl body. While this location precluded identifying fish orientations at the mouth of the trawl, it was not possible to separate the anterior trawl body because of the different mesh sizes in the upper (146.3 mm SMO) and lower (92.5 mm SMO) panels. A horizontal-separator panel at this location might have confounded selection by separating and concentrating fish adjacent to two different-sized meshes. Nevertheless, in one of the few relevant studies, Ferro et al. (2007) showed no significant effects of panel length (starting 11.0 and 19.5 m posterior to the ground gear) on various diverse species and their sizes, including Atlantic cod, haddock, saithe, *Pollachius virens*, whiting, *Merlangius merlangus*, and monkfish, *Lophius piscatorius* in a slightly longer North Sea trawl comprising identical SMO throughout. And other studies have used relatively shorter separating panels with meaningful results (e.g. He et al., 2007; Krag et al., 2009). Consequently, we assume there should be consistency in the observed orientations of fish throughout much of the trawl body assessed here.

A final important consideration in interpreting the data, is that the two treatments of interest (horizontal-separator panel and dual codends only) were temporally confounded within experiments (which is often unavoidable, e.g. Ferro et al., 2007). It was not possible to randomise their testing, and it is clear that factors other than the treatments of interest explained some variability in catches (e.g. a significant main effect of experiment and/or depth for some variables). However, the significance of codend effects and the interaction with experiment facilitate interpolations and relative comparisons.

There was considerable species-specific variability (less so for size) among vertical orientations observed here, which supports the general trend in the literature (Winger et al., 2010). Nevertheless, there were broad consistencies among some groups. In particular, as for several overseas species (e.g. haddock and whiting), here the commercially important and semi-pelagic yellowtail scad and longfin bigeye, and non-commercial barracouta remained high in the posterior trawl body, while most unwanted stingrays, skates and stingarees tended to remain lower (Winger et al., 2010). Also, comparable to observations among other squid (e.g. longfin inshore squid, *Doryteuthis pealeii* off the eastern USA; Bayse et al., 2016), the Gould's squid here apparently entered the mid trawl at varying heights, but mostly higher, and then maintained a preference for a higher orientation as they progressed aft.

The same upward tendency in the trawl applied to most remaining species (although these entered the mid trawl mostly below the horizontal-separator panel) and is supported by previous studies

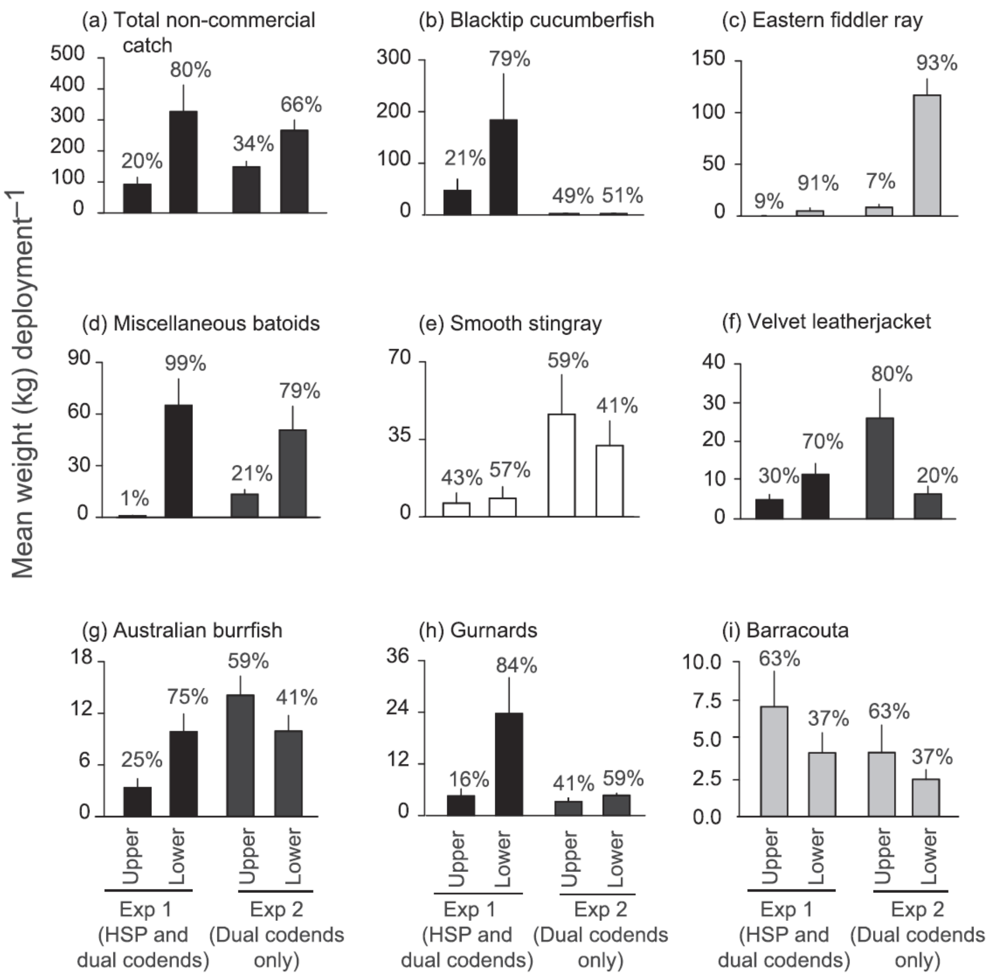

Fig. 5. Non-commercial groups/species (in order of abundance): mean (+SE) weights deployment^{-1} separated by experiment and codend of (a) total catch, (b) blacktip cucumberfish, *Paraulopus nigripinnis*, (c) eastern fiddler ray, *Trygonorrhina fasciata*, (d) miscellaneous batoids, (e) smooth stingray, *Bathytoshia brevicaudata*, (f) velvet leatherjacket, *Meuschenia scaber*, (g) Australian burrfish, *Allomycterus pilatus*, (h) gurnards, *Lepidotrigla mulhalli* and *L. modesta* and (i) barracouta, *Thyrsites atun*. Percentages above histograms are contributions to total catch. All black, grey or white histograms indicate a significant interaction (experiment × codend), main effect of codends or no significant gear effects, respectively (Tweedie generalized linear mixed models, $p < 0.05$).

assessing the utility of 'escape' panels of mesh with larger, more consistent lateral openings (T0, T45 or T90) typically located in the tops of fish- and crustacean-trawl extensions/codends (Broadhurst, 2000; Kennelly and Broadhurst, 2021). For example, Broadhurst and Kennelly (1997) and Broadhurst et al. (2002) showed panels of T45 mesh located on the tops of extensions in nocturnally fished south-eastern Australian penaeid-trawl codends allowed various species and their sizes to escape, including congenerics and species caught here such as gurnards, leatherjackets, *Paramonacantus filicauda*, red bigeye, *Priacanthus macracanthus*, john dory and other flatheads, *Ratabulus diversidens* and *Platycephlaus longispinis*. Nevertheless, there are additional stimuli associated with crowding, water flow and available light that affect fish behaviour in codends (Winger et al., 2010), considering Broadhurst et al. (2002) observed eastern school whiting also readily escape codends via top panels at night, but in the present study, the species trended downwards at the posterior body during diurnal deployments.

While the data here facilitate a general understanding of the vertical orientation of various species, the absence of direct observations precludes quantifying any species- or size-specific swimming directions, velocities and reactions in the posterior trawl or codends—information that remains limited for regional species. Nevertheless, when considered collectively, the data support some general consensus. Specifically, in one of the few studies using video to quantify fish reactions in regional trawls, Piasente et al. (2004) observed jackass morwong, *Nemadactylus macropterus* in a trawl displayed haphazard behaviour, ranging from motionless to burst speeds, but like grey morwong caught in the present study, also remained low throughout capture.

Piasente et al. (2004) also noted tiger flathead mostly remained low and passed through the trawl at cruise (steady tail beat) swimming speeds before entering the codends either facing the direction of towing or aft. Yanase et al. (2009) observed limited reactions to trawls by another platycephalid (southern sand flathead, *Platycephlaus bassensis*), although consistent with the results here, most individuals remained low in the trawl body. The bias observed here towards more larger tiger flathead in the lower posterior trawl during experiment 1 could support an active swimming response, considering fish swimming speeds are positivity related to their TL (Beamish, 1978). The same argument might also support the bias towards larger john dory in the upper trawl, assuming their preferred response is to swim upwards as they approach the extension. Any size effects did not extend to the other species

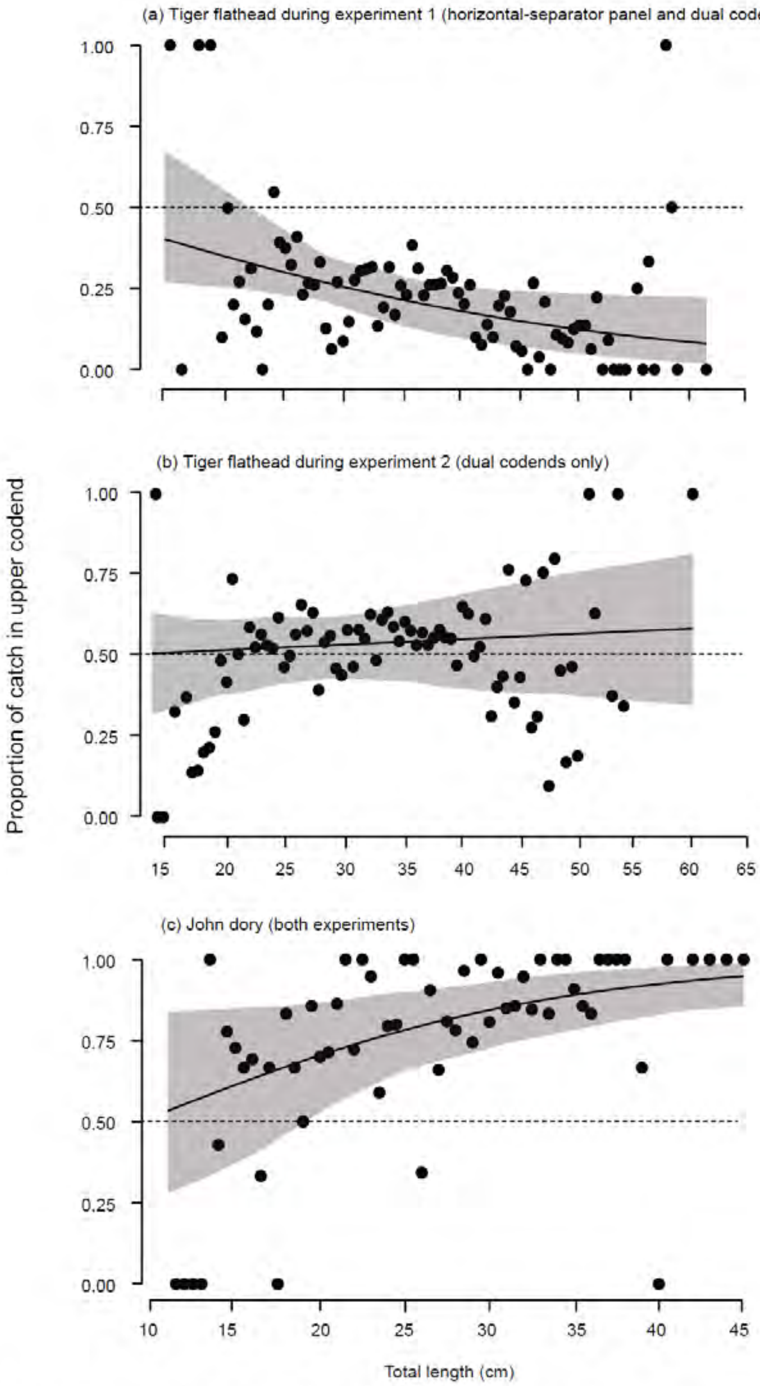

Fig. 6. The proportions of catch by total length entering the upper codend for tiger flathead, *Platycephalus richardsoni* in experiments (a) 1 and (b) 2; and (c) john dory, *Zeus faber* (both experiments combined). Points show the observed proportions, dashed line is 0.5 equal probability, solid line is the fitted logistic regression, and the shaded areas are 95% confidence intervals.

assessed for any influences, including blacktip cucumberfish, gurnards or velvet leatherjack, although for some, their size ranges were relatively smaller than either tiger flathead or john dory. Further in situ observations are required to closely assess any size-specific effects on vertical orientations in the posterior body and what this means in terms of improving selection.

Notwithstanding considerable similarity in vertical orientations among commercial and non-commercial species, the data do support some broad starting points for improving trawl efficiencies, which not only encompasses species selection, but also engineering performances. First, many commercial species, and especially the most abundant caught here, including tiger flathead, silver trevally, southern sawshark, and eastern angel shark mostly enter the lower posterior trawl, and so it should be possible to fish either lower-opening trawls and/or increase mesh size in the upper anterior panels. Because many fish then rise up in the posterior trawl, increasing mesh size at this location might also be possible. Doing so would probably not affect species selectivity greatly (and therefore not reduce bycatch), but such modifications would reduce drag and therefore fuel usage (and help to maintain otter-board spread for the existing configuration tested here).

Second, because many commercial teleosts mostly rise up in the posterior trawl, while most non-commercial elasmobranchs remain relatively lower, it might possible to exclude the latter via modifications to the lower sections of the trawl (including the ground gear and lower body panel), or (under some conditions) even bottom-opening grids in the posterior body/extension. Most of the unwanted elasmobranchs were larger than the retained species, and their exclusion would dramatically improve trawl selection, which is a priority for some areas. Specifically, concern about declines in some elasmobranch populations on trawl fishing grounds off the NSW coast (e.g. southern dogfish, *Centrophorus zeehaani* and Harrisson's dogfish, *C. harrissoni*; Graham et al., 2001) has seen them listed as "conservation dependent" under Australia's Environment Protection and Biodiversity Conservation Act. With the decline mostly attributed to trawling, modifications that reduce catches of unwanted elasmobranchs while maintaining target catches would be beneficial for managing the CTS fishery.

Regardless of trawl modifications, it is essential their design and future testing are done in close consultation among fishers. Unless there is ratified support for subtle changes to trawl designs, their recommendation will mean little. The widescale use of subtle modifications that even only marginally improve in selection will have greater long-term benefit than restricted use of more ambitious technical changes to trawls.

CRediT authorship contribution statement

Matt K. Broadhurst: Conceptualization, Data curation, Funding acquisition, Investigation, Methodology, Project administration, Resources, Software, Supervision, Validation, Visualization, Writing - original draft, Writing - review & editing. **Ian A. Knuckey:** Conceptualization, Investigation, Methodology, Supervision, Visualization, Writing – review & editing. **Russell B. Millar:** Methodology, Software, Visualization, Data curation, Formal analysis, Validation, Writing - review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data Availability

Data will be made available on request.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.fishres.2023.106618.

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Appendix 9. Broadhurst, M.K., Knuckey, I.A. and Millar, R.B. 2023. Relative selectivity of T90 codend sections on a fish trawl in the Great Australian Bight. Full report of fishing trials done over ten days during November 2022 on FV Explorer

Relative selectivity of T90 codend sections on a fish trawl in the Great Australian Bight

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Abstract

The effects of increasing both the size and area of meshes turned 90º (termed 'T90')—to increase lateral openings—in the codend of an Australian fish trawl were investigated to improve size selection of the key target, deepwater flathead, *Neoplatycephalus contas* (≥40 cm total length, which corresponds to size at maturity) and reduce catches of discarded species. The conventional codend comprised nominal 94-mm mesh throughout with normal orientation in the posterior half, but T90 in the anterior half ('half 94-mm T90' codend). The second and third codends had 105-mm T90 mesh in the anterior section only ('half 105-mm T90') and throughout the entire codend ('full 105-mm T90'), respectively. Both new codends improved size selection for deepwater flathead, although the full 105-mm T90 reduced catches of individuals ≥40 cm TL. The new T90 designs also allowed some discarded species to escape, but similarly affected other targeted species. Data collected describing the morphology of deepwater flathead supports further testing a T90 mesh size of ~100 mm in the anterior codend, or ~94-mm throughout to maintain target catches (≥40 cm TL). But, irrespective of any changes to codend meshes, owing to comparable inter-specific sizes and shapes, the percentage of discards in this fishery will remain consistent. This outcome is supported by additional data collected from an 85-mm conventional diamond-mesh codend fished after the experiment which, notwithstanding confounded spatial and temporal deployments and despite retaining more smaller deepwater flathead, maintained a comparable percentage of total discards (i.e. ~70% of the total catch). The observed discarding in the fishery (mostly non-commercial species) was more than double the global average for similar gears, which supports future research to investigate trawl modifications other than codend changes to improve species selection.

Introduction

Trawling for fish is among the world's oldest mechanised, and most common, fishing methods, producing some 25 million t of seafood each year, or nearly one quarter of the global marine production (Pérez Roda et al., 2019; Pauly et al., 2020). Notwithstanding their importance, most fisheries involve multiple target species of varying morphologies and sizes, which can debase trawls to less-than-ideal selection and cause large subsets of catches to be discarded. The mortality of these discards raises concerns over unwanted environmental impacts (Kennelly and Broadhurst, 2021).

Various options are available for improving the selectivity of fish trawls, although >70% of efforts have focused on the codend (where catches accumulate) and historically by legislating appropriate diamond-mesh sizes (Kennelly and Broadhurst, 2021). In recent decades, efforts at improving codend selectivities have extended to regulating other factors known to affect lateral-mesh openings (regardless of mesh size), including: excessive twine diameter (Lowry and Robertson, 1996; Herrmann and O'Neill, 2006); codend circumferences (Reeves et al., 1992; Graham et al., 2009); or different orientations of mesh (Kennelly and Broadhurst, 2021). The latter initially involved turning conventional diamond-shaped (termed 'T0') meshes 45^{o} to create 'square mesh' or 'T45' (Roberstson and Stewart, 1988; Millar and Walsh, 1992), but more recently, 90 degrees to form 'T90' mesh (Moderhak, 1997). Ancillary modifications to further maintain lateral openings (for any configuration of mesh) include lastridge ropes, which are often slightly shorter than the stretched length of the codend (e.g. Ingólfsson, and Brinkholf, 2021).

Most of the work to improve fish-trawl selectivity has occurred in Europe and North America (Kennelly and Broadhurst, 2021). Fewer efforts have occurred in the southern hemisphere, including Australia (~3% of global efforts) where there are currently 14 separately managed fish-trawl fisheries and ~135 licences (Broadhurst et al., 2022; 2023). Among these fisheries, the most important are based in southern half of the continent, including the Great Australian Bight. This fishery targets eight key commercial species (which comprise 77% of the total retained catch) but >50% often includes deepwater flathead (*Neoplatycephalus conatus)* and bight redfish (*Centroberyx* gerrardi). In addition to these targets, > 300 species are discarded; 42 of which represent 90% of the total discarded weight, and often latchet (*Pterygotrigla polyommata*) which is edible, but also stingarees (*Urolophidae* and *Plesiobatidae*) that have no potential commercial value (van Putten et al. 2019).

Recently, in an attempt to reduce unwanted bycatches and following overseas success (Ingólfsson and Brinkholf, 2020), operators in one Australian fishery trialled codends comprising anterior sections (~50% of the codend) of T90 mesh made from the existing conventional meshes used in codends (minimum legal stretched mesh opening; SMO of 90 mm). We formally assessed the utility of this 'half 94-mm T90' codend against a traditional diamond-mesh ('T0') design (Broadhurst et al., 2022). There were no effects of the T90 codend on selection for the key target, deepwater flathead, or other retained species (e.g. ocean jackets, *Nelusetta ayraudi*, yellow spotted boarfish, *Paristiopterus gallipavo* or red gurnard, *Chelidonichthys kumu*), but the half 94-mm T90 codend also failed to exclude catches of any smaller non-target species, including latchets, which accounted for 23% of discards (Broadhurst et al., 2022). The lack of improved selectivity was attributed to the mesh size being too small (irrespective of orientation). The half 94-mm T90 codend did slightly improve the visual quality of deepwater flathead, attributed to the more consistent openings allowing sand and debris to fall out of the codend (Broadhurst et al., 2022).

Deepwater flathead are regulated via a total allowable catch (~1238 t for 2022/23), but there is no size limit in place. Fishers generally target fish > 40 cm total length (TL), which is assumed to be the size at maturity (Tuck, 2018). Ideally, smaller conspecifics would not be caught but when they are, they are usually discarded. Although no morphological data are published, like all other platycephalids (Broadhurst et al., 2006), deepwater flathead are ventrally compressed (maximum height-to-depth ratio approaching ~0.6). This body shape corresponds to the general orientation of a T90 mesh which might imply possibilities for escape, assuming an appropriate mesh size (Broadhurst et al., 2006).

Owing to few fish trawlers in Australia, there are limited regional opportunities for purchasing appropriate mesh sizes for codends (in adequate twine diameters) with products typically sold in 10-mm increments. Beyond 90- to 95-mm mesh, the next available material in similar twine diameters is ~105 mm. This material is also sold in slightly narrower twine diameters, which, based on the known relationships between twine diameter and selectivity (Lowry and Robertson, 1996; Herrmann and O'Neill, 2006), should improve selection for any given T90 mesh size.

Intuitively, selectivity might further be improved by including T90 throughout the codend, rather than just the anterior section. Considering the above, the aims here were to fish a conventional trawl in the Great Australian Bight, alternately rigged with a conventional T90 codend, comprising ~94-mm diamond-shaped mesh in the posterior and T90 in the anterior sections described by Broadhurst et al. (2022) and two new designs of T90 codends. The first comprised 94-mm diamond-shaped mesh in the posterior section, but 105-mm of T90 in the anterior section, while the second made entirely 105-mm T90 throughout. We sought to test the hypothesis that the new codends would maintain catches of deepwater flathead ≥40 cm TL and ventrally compressed by-product species but reduce catches of small deepwater flathead, and one of the key discards, latchets, *Pterygotrigla polyommata*.

2. Methods

The experiment was done in the Great Australian Bight, Australia (33.12°S; 128.06°E to 33.27°S; 129.40°E) during a single trip comprising eleven consecutive days and nights from 30 October to 9 November, 2022 using the FV "Explorer S" (35 m and 500 Kw). The vessel was rigged with its conventional, single two-seam trawl (41-m headline, with nominal 152- and 120-mm SMO in the wings and body) attached to 20- and 200-m bridles and sweeps and spread by steel V-otter boards. The posterior trawl body (100 meshes in the transverse direction–T) was configured to enable different extensions and codends to be attached (below). The vessel had a Scanmar trawl monitoring system to measure otter-board spread (m), a Lowrance global positioning system (GPS) to record distance fished (m) and speed over the ground (SOG m^{-1}), and a Furuno echo sounder for fishing depth (m).

2.1. Extensions and codends

Three new four-panel extension and codend sections (all the same lengths) were built for the work using up to four sheets of knotted polyethylene (PE) braided netting; each of which was measured for at least 20 replicate mesh sizes using a purpose-built gauge and verified with vernier callipers (Fig. 1a–b). The extension sections were all made from a mean (±SE) mesh size of 105.9 (0.18)-mm SMO (3-mm diameter–Ø twine) orientated as T0 and measuring 24.5 meshes in the normal (N) direction and 100 T). Four lastridge ropes (24-mm Ø twisted polypropylene–PP) were attached at the seams of the extension sections and measured the same stretched length (Fig. 1). Three different four-panel codends (all made using double-twine netting; below) were attached to the ends of the identical extension sections (Fig. 1).

The first codend (half 94-mm T90) was the same design as that tested by Broadhurst et al. (2022) and comprised an anterior section of 93.8 (± SE of 0.17) mm SMO (4-mm Ø double twine) turned 90º sewn across the four panels for a total of 66 meshes in circumference × 50 meshes deep (Fig. 1a). Four 16-mm Ø Dynema lastridge ropes were attached at the junction of each panel and were 17% shorter than the stretched anterior codend length (Fig. 1a). The T90 section was attached to a posterior T0 codend section measuring 25 N × 100 T and made from the same mesh as above, with longer lastridge ropes that measured the same length as the stretched meshes (Fig. 1a).

The second codend (termed 'half 105-mm T90') had the exact same posterior section as the half 94-mm T90, but an anterior section made from four panels of ~104.5 (± 0.19)-mm SMO T90 mesh (3-mm Ø double twine) totaling 60 meshes around × 45 meshes long (Fig. 1b). Four lastridge ropes were attached as above. The third codend ('full 105-mm T90') had the same T90 anterior section as the second, but differed in the posterior section, which was also made from T90 mesh with an SMO of 103.4 (± 0.21) mm (4-mm Ø double twine) and totalling 60 meshes in circumference × 37 meshes long (Fig. 1 c). Four shorter (by 17%) lastridge ropes extended throughout both codend sections (Fig. 1c).

The skipper of the vessel also had a complete T0 configuration on board with the same length and width as that tested by Broadhurst et al. (2022) (termed the 'full 85-mm T0' here; Fig. 1d). The extension had the same dimensions as above while the codend (4-mm Ø double twine) measured 100 T × 54.5 N a(Fig. 1d). Four lastridge ropes the same length as the extension and codend were attached to the seams. This configuration had a mean mesh size (±SE) of 102.6 (±0.2) mm and 84.8 (± 0.6) mm SMOs in the extension and codend (double twine), respectively (Fig. 1d).

2.2. Testing and sampling

The original, agreed sampling design with the fishing company was to alternately attach the three T90 codends (and their extensions) to the trawl and fish these across similar depths and locations over four deployments every 24 h, during a 12-day cruise (i.e. 12 replicates of each treatment). However, this was not achieved, and after six or seven replicates of each codend (over seven days), the skipper removed all new codends and attached the full 85-mm T0 codend, which was fished for all remaining deployments (see Results).

Irrespective of the codend, data were collected during fishing, on the: fished location; distance (km) and duration (h; winch brakes on and off); otter-board spread (m); SOG (ms^{-1}); and depth (m) of the trawl. The latter three variables were logged every ~15 min to provide an average deployment^{-1}. After retrieval, the codend was emptied into an area with a measured volume, and the total catch weight estimated. Retained catches were separated and boxed before weighing and counting. The total weight of discarded catch (bycatch) was estimated by subtracting the retained component from the total catch. A subsample of discards was then assessed. All discards were then individually counted and weighed in the subsample and extrapolated to the totals. Randomly selected subsamples of key species, and predominantly deepwater flathead and latchet (up to 130 deployment^{-1}), but also some samples of others were measured to the nearest 0.5 cm (TL for fish and disc width; DW for stingarees).

During three randomly selected deployments, a subset of 102 of deepwater flathead were collected and immediately measured for their TLs and maximum heights (MH), widths (MW) and girths (MG; all to the nearest 1 mm). The MH and MW were recorded using vernier callipers, while MG was taken by wrapping a length of polyamide (~1-mm Ø) around the thickest part of each fish, and then measuring this.

2.3. Statistical analyses

Formal analyses were restricted to the data for the three T90 codends only (i.e. these were tested across approximately the same space and time), but mean catches for the smaller-meshed full 85-mm T0 codend tested during the second half of the cruise are nevertheless presented for comparative purposes. Data describing otter-board spread were analysed using linear mixed models (LMM) that included the fixed effects of 'codend configuration' (the three T90 codends only), and the co-variates 'depth' and 'SOG'. 'Days' was included as a random term. A backward-selection algorithm was employed with non-significant fixed terms removed until the remaining terms were significant.

Standardized (ha^{-1} trawled) weights of key species and combined catches were analysed using the Tweedie distribution (which innately incorporates zero inflation in non-negative numeric data and is fitted on the log scale) fitted using a generalized linear mixed model (GLMM). The Tweedie GLMM was fitted using the glmmTMB function from the R package of the same name. As above, codend configuration was considered fixed, while days were random. The statistical significance of fixed effects was evaluated at the 5% level using Wald tests, and any significant effects of codend configuration were separated using false discovery rate (FDR) pairwise tests.

In addition to the mixed-effects models, generalized additive modelling (GAM) was used to fit relative selectivity curves to the length-frequency data of species caught and measured in sufficient numbers, which was restricted to deepwater flathead and latchet. Length frequencies were first scaled up by tow subsampling fractions to estimate total frequencies. Relative selectivity was assessed for each of the three possible pairings of the three gears. For example, for those tows involving the half 94-mm T94 and half 105-mm T90 codends, let n_l^{H94} and n_l^{H105} denote the number of length *l* fish caught in those gears. Then

$$p_l = \frac{n_l^{H105}}{n_l^{H94} + n_l^{H105}}$$

is the proportion caught in the H105 gear. The expected value of p_l was modelled on the logit scale using cubic regression splines of dimension three, denoted *s(l)*. That is

$$E[p_l] = \frac{\exp(s(l))}{1 + \exp(s(l))}$$

The error distribution of p_l was specified to be quasi-binomial to incorporate overdispersion arising from subsampling of catches. The GAMs were fitted in R using the gam function within the mgcv package (Wood, 2017). Confidence intervals around the fitted splines were obtained using a 1000 iteration double bootstrap (Millar, 1993; Xu and Millar, 1993) whereby the relevant tows were first resampled, followed by resampling of the length frequencies within each selected trawl. This catch-comparison analysis was implemented using the SELECT R package which includes bootstrap functionality to allow for between-haul variability (Millar et al. 2004; 2021). A permutation test was also used (1000 resamples) to assess for any statistical significance of codend configuration (Broadhurst et al., 2022).

The morphometric data (MW, MH and MG) for the sampled deepwater flathead were pooled across deployments. These data were fitted as linear regressions (using least squares) indexed against TL and graphed.

3. Results

The various sections of netting showed minimal intra-panel variability (measured as SE) in SMO, except for the full 85-mm T0 codend (Fig. 1). In total, the four codends were fished during 30 deployments (six for the half 94-mm T90 codend; seven for each of the other T90 codends and 10 for the 85-mm T0 codend) across comparable mean (± SE) durations (5.02 ± 0.02 h), depths (145.9 ± 3.1 m) and SOGs (1.6 ± 0.0 ms^{-1}). Neither otter-board spread (154.6 ± 1.0 m) nor swept area (451.7 ± 4.4 ha) were significantly affected by codend (LMM, p > 005), but the former did significantly increase with fishing depth (LMM, $p < 0.001$).

Across the four fished codends, a total of 59 t was caught; of which 15 t (25% of the total) was retained for sale and the remaining 75% discarded (Table 1). More than 67 species were caught, but only eight species were caught in sufficient numbers to warrant analyses among the T90 codends, including: latchet (99% of which were discarded); deepwater flathead (none discarded); ocean jacket (31% discarded); southern fiddler ray; *Trygonorrhina dumerilii* (100% discarded); yellowspotted boarfish (0% discarded); Australian burrfish, *Allomycterus pilatus* (100% discarded); red gurnard, *Chelidonichthys kumu* (1% discarded); and ringed toadfish, *Omegophora armilla* (100% discarded) (Table 1). Among the measured species, all encompassed comparable sizes (Table 1).

3.1. Relative species selectivity

The Tweedie GLMMs detected significant effects of codend configuration among the weights of retained total catches and deepwater flathead (both for those ≥ and <40 cm TL) and discarded latchet and ringed toadfish ($p < 0.05$; Table 2, Figs 2a, b and c and 3b and d). Nevertheless, the weights of retained yellowspotted boarfish and red gurnard returned p-values of 0.08 and 0.06, respectively (GLMM, Table 2). While all variables showed the same trend of progressively lower weights in the half and then full 105-mm T90 codends than the conventional half 94-mm T90 codend, significant separation of means via FDRs was restricted to the total retained catch and both categories of deepwater flathead (Fig. 2a–c).

Specifically, compared to the half 94-mm T90 codend, both larger-meshed T90 codends had similar, significantly lower total retained catches (FDR, $p < 0.05$; Fig. 2a). For deepwater flathead, compared to the half 94-mm T90 codend there was no significant difference in the weight of individuals ≥ 40 cm TL caught in the half 105-mm T90 codend (FDR, $p > 0.05$), but there was in the full 105-mm T90 codend (FDR, $p < 0.05$; Fig. 2b)—although the latter two codends had statistically similar catches (FDR, $p > 0.05$; Fig. 2b). Clearer differences were observed for small deepwater flathead, with incrementally significant reductions by the half and full 105-mm T90 codends (FDR, $p < 0.05$; Fig. 2c).

Irrespective of analyses of catches within T90 codends, for many variables the full 85-mm T0 codend had comparable mean catches as the half 94-mm T90 codend (Figs 2 and 3). The clear exceptions were for retained red gurnard (lower mean weight) and discarded latchet (lower) and small deepwater flathead (greater mean weight) (Figs 2 and 3).

3.2. Relative-size selectivity

Relative size-frequency plots between codends showed that compared to the conventional half 94-mm T90 codend, there were relatively fewer deepwater flathead <40 cm TL retained in the full 105-mm T90 codend (Fig. 4a and b). The half 105-mm T90 and full 85-mm T0 codends retained similar proportions of small deepwater flathead (Fig. 4c and d). For latchet, there were no clear differences in relative size-frequency distributions retained among any of the codends (Fig. 4b, d, f and h).

Cubic spline catch probability curves were successfully fitted to all three relative comparisons of the T90 codends for deepwater flathead and latchet (Fig. 5). Permutation tests detected significant TL effects for deepwater flathead in both 105-mm T90 codends vs the half 94-mm T90, and for latchet in the full vs the half 105-mm T90 codends ($p < 0.05$; Fig. 6a,c and f). For deepwater flathead, the significance manifested as proportionally more smaller fish (<~55 cm TL; albeit with considerable variability) escaping from the codends comprising 105-mm T90 mesh, and especially the full 105-mm T90 codend (Fig. 5a and c). Among latchet, proportionally more individuals < ~40 cm TL escaped from the full 105-mm T90 codend when compared to the half 105-mm T90 codend.

3.3. Deepwater flathead morphology

Significant linear regressions were derived between the TL and MH, MW and MG for deepwater flathead with total length explaining 83–92% of the variation in cross-sectional morphometrics ($p < 0.001$, Fig. 6). For fish at 40 cm TL, the MH, MS and MG were 35, 64 and 170 mm, respectively (Fig. 6). Considering the maximum mesh perimeter of a 105-mm SMO mesh (~210 mm; notwithstanding variable knot thickness due to twine diameter), this corresponds to a deepwater flathead measuring ~47.5 mm TL.

4. Discussion

This study reiterates that slight increases in T90 mesh size and/or area can considerably improve species-specific size selection (İlhyaz et al., 2017; Veiga-Malta et al., 2019; Cheng et al., 2020). Further, while there were relatively fewer deployments than planned, the changes in size selection for deepwater flathead were reasonably correlated to their morphology which supports maintaining larger mesh openings (via the lastridge ropes) in the four-panel codends. There was, however, some variability that appeared to increase with T90 mesh area (e.g. the full 105-m T90 codend allowed a greater range of sizes to escape). Both larger-meshed T90 codends also caught less discards, although like for other multi-species fisheries (e.g. Sola and Maynou, 2018; Cheng et al., 2020; Robert et al., 2020) there were concomitant reductions in catches of some desired species, which cumulatively reduced total retained catches. The utility of T90 in the studied fishery can be discussed by considering the morphology of deepwater flathead (and their prioritization in terms of reducing fishing mortality) along with similar sizes of individuals among retained and discarded species. Ultimately, this information might be used to suggest other refinements to regional trawls to improve selection (Broadhurst et al., 2023).

The potential for any fish to escape through a mesh requires sufficient contact (often repeated), and cross-sectional dimensions smaller than the mesh openings, and ultimately the mesh perimeter. Based on the morphological data collected here, like all other platycephalids, deepwater flathead have a MW-to-MH ratio of ~0.5 which corresponds well to the shape of a T90 mesh held open by lastridge ropes in a codend (Broadhurst et al. 2006). In this study, the 105-mm meshes were hung at 66% of the extension circumference and would have remained open to their perimeter of ~210 mm. Assuming sufficient contact, deepwater flathead measuring up to ~47.5 mm TL could pass through, although variable condition and/or their soft-tissue compression would mean some slightly larger fish would still squeeze through, while other smaller fish might not. This estimated size of fish is somewhat supported by the modelled relative selectivity curves for the two larger-meshed T90 codends vs the conventional design, but clearly was not the only variable accounting for the probability of fish escaping, given the relatively greater reductions in catches of deepwater flathead <40 cm TL by the full 105-mm T90. Presumably, increasing the amount of open meshes through the codend in the area where deepwater flathead had the greatest probability of repeatedly encountering meshes (immediate anterior to the catch), increased their escape.

Some evidence of differences between the larger-meshed T90 codends imply a full T90 codend (or possibly the posterior section only) with a slightly smaller mesh size may be more appropriate for regulating the size of deepwater flathead retained. In our earlier study, we showed no effects on size selection of deepwater flathead for a codend comprising 94-mm T90 mesh in the anterior section only (Broadhurst et al., 2022). The smaller mesh corresponds to the girth of a deepwater flathead measuring ~39.4 cm TL and so extending 94-mm T90 mesh throughout the codend might allow at least some deepwater flathead <40 cm TL to escape. Alternatively, increasing the T90 mesh size to ~100 mm in the anterior section only—corresponding to a deepwater flathead ~41.6 cm TL but assuming less probability of contact—might have some benefit.

However, notwithstanding any improvements to size selection for deepwater flathead associated with increasing either the size or area of any T90 mesh, the similar sizes of other species mean there will probably be cumulative reductions in other catches—and not only among discards, but also some targets. The two discard species most strongly affected by the larger-meshed T90 codends here were latchet (of which larger fish might be retained) and ringed toadfish (always discarded). No data are available on their morphologies, but both are approximately fusiform (MH-to-MW ratio of ~1), and like for deepwater flathead, smaller individuals were able to escape, especially from the full 105-mm T90 codend. Among the dominant retained species, red gurnard is similarly fusiform, and while there was no significant reduction in their catches by the larger-meshed T90 codends, relatively fewer were retained in the full 105-mm T90 codend. Based on morphometric data collected for smaller fish by Broadhurst et al. (2006), red gurnard with a girth of 210 mm (i.e. matching the 105-mm mesh) might measure ~37.5 cm TL, but individuals are retained down to ~<25 cm TL and so at least some smaller fish could escape. In contrast, ocean jacket and yellowspotted boarfish (other retained species) are ventrally compressed, which might have limited the escape of many, although their mean catches were lower in the larger-meshed T90 codends. Some loss of these species (along with relatively lower catches of deepwater flathead <40 cm TL) contributed to the observed reduction in total retained catches.

It is clear that in terms of total discards (which comprised 75% of the total catch here), and notwithstanding relatively few replicate tows, larger T90 mesh isn't going to be an effective gear modification beyond allowing some small deepwater flathead to escape and potentially slightly improving quality of the retained catches (Broadhurst et al., 2022). And it remains unclear if other, simpler codend modifications within existing configurations would have the same selective utility; testing of which should be promoted before more complex alternatives within a coherent protocol (Broadhurst et al., 2007). For example, although not as novel or marketable as T90 mesh, simply using larger T0 mesh with or without or shortened lastridge ropes might have sufficient benefit (Sistiaga et al., 2021). Certainly, while alternative modifications should be encouraged, especially if they are industry developed, these nevertheless should be compared against simpler options. One example of the problems of not following this protocol involves complex size-sorting grids in Barents Sea fish trawls (with 135-mm T0 mesh codends) which were mandated after testing to improve selection for cod, *Gadus morhua* during the late 1990s. However, Jørgensen et al. (2006) subsequently concluded that simply increasing the conventional T0 mesh to 155 mm (without a grid) provided the same selection benefits, and certainly at a lower cost and complexity.

Regardless of appropriate mesh size or shapes in the codend to regulate the fishing mortality of deepwater flathead, given the amount of discarding, and not withstanding some possibility of future markets for latchets, other simple gear modifications warrant assessment. Recently, using a separator panel in another Australian fish trawl, Broadhurst et al. (2023) recorded species-specific differential vertical orientations among key species as they passed through the posterior trawl. It might be feasible to assess a similar concept to determine if the key discarded species here could be anteriorly separated by exploiting their behaviour during capture. Possible options include raising the footrope and/or modifying the ground gear and associated stimuli (e.g. light) (Kennelly and Broadhurst, 2021). Mechanical excluders near the codend to exclude larger stingarees (e.g. >30 cm DW) could also have some utility.

Removing excessive quantities of larger unwanted catches like wide stingarees might also help improve selection in the posterior trawl, because these can mask and reduce the effectiveness of openings (Kennelly and Broadhurst, 2021). Ongoing work is certainly required considering the discard rates for the both conventional half 94-mm T90 and full 85-mm T0 codends were more than twice the global average for fish trawls (~30%; Pérez Roda et al., 2019). The data along with those from previous short-term fishing gear assessments (~67% discards; Broadhurst et al. 2022) might imply the fishery is among the least selective on the planet, which might support a high regional priority for resolution. Clearly, any future efforts require close collaboration and support from industry to test alternatives, and ultimately to realise changes to the trawls that achieve goals beyond operational benefits (i.e. improved catch quality) extending to ongoing sustainable harvesting, with minimal collateral impacts.

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Table 1. List of species caught and %discarded during 30 deployments of four codends in the Great Australian Bight during November, 2022.

Species	Wt (kg)	No.	% discarded (wt)
Latchet, *Pterygotrigla polyommata*	26227.1	136203	99
Wide stingaree, *Urolophus expansus*	10126.1	20912	100
Deepwater flathead, *Neoplatycephalus conatus*	6175.5	7632	0
Ocean jacket, *Nelusetta ayraudi*	3775.3	9298	31
Southern fiddler ray, *Trygonorrhina dumerilii*	3418.4	825	100
Yellowspotted boarfish, *Paristiopterus gallipavo*	1101.5	703	0
Gummy shark, *Mustelus antarcticus*	1037.0	323	0
Australian burrfish, *Allomycterus pilatus*	1022.0	1691	100
Jackass morwong, *Nemadactylus macropterus*	1014.2	3261	87
Ornate angelshark, *Squatina tergocellata*	752.7	150	1
Gould's squid, *Nototodarus gouldi*	680.3	1216	1
Red gurnard, *Chelidonichthys kumu*	474.7	735	1
Greeneye dogfish, *Squalus chloroculus*	473	169	100
Bight redfish, *Centroberyx gerrardi*	391.5	280	0
Ringed toadfish, *Omegophora armilla*	339.4	1105	100
Port Jackson shark, *Heterodontus portusjacksoni*	191	37	100
Knifejaw, *Oplegnathus woodwardi*	171.9	331	21
Smooth stingray, *Dasyatis brevicaudata*	149	21	100
Common gurnard perch, *Neosebastes scorpaenoides*	140.8	295	100
Western shovelnose ray, *Aptychotrema vincentiana*	140.2	69	100
Spotted wobbegong, *Orectolobus maculatus*	130.0	3	0
Bronze whaler, *Carcharhinus brachyurus*	120.0	1	0
Southern eagle ray, *Myliobatis tenuicaudatus*	109.0	8	100
Tusk, *Dannevigia tusca*	101.0	74	0
Swallowtail, *Centroberyx lineatus*	99.3	732	100
Deepwater stargazer, *Kathetostoma nigrofasciatum*	88.9	311	100
Barracouta, *Sphyraena novaehollandiae*	87.9	331	100
Blue morwong, *Nemadactylus valenciennesi*	87.0	21	0
John dory, *Zeus faber*	76.3	44	0
Jack mackerel, *Trachurus declivis*	62.5	647	100
Spikey dogfish, *Squalus megalops*	60.8	90	100
Blackspot boarfish, *Zanclistius elevatus*	46.0	129	24
Banded wobbygong, *Orectolobus halei*	40.0	1	0
Melbourne skate, *Spiniraja whitleyi*	40.0	2	100
Bighead gurnard perch, *Neosebastes pandus*	39.7	85	100
Thetis fish, *Neosebastes thetidis*	34.4	106	100
School shark, *Galeorhinus galeus*	32.6	11	0
Fourspine leatherjacket, *Eubalichthys quadrispinis*	25.9	32	76
Ocean perch, *Helicolenus percoides*	20.0	126	100
Cosmopolitan rubyfish, *Plagiogeneion rubiginosum*	16.7	251	100
Blackspotted gurnard perch, *Neosebastes nigropunctatus*	16.3	29	0
Cuttlefish, Sepiidae	15.9	57	100
Broadnose shark, *Notorynchus cepedianus*	14.0	2	0
Southern rock lobster, *Jasus edwardsii*	12.8	13	100
Harpuku, *Polyprion oxygeneios*	12.0	2	0
Whitebarred boxfish, *Anoplocapros lenticularis*	11.4	27	100
Mosaic leatherjacket, *Eubalichthys mosaicus*	10.4	9	100
Footballer sweep, *Neatypus obliquus*	10.1	25	100
Bigeye ocean perch, *Helicolenus barathri*	8.4	18	100
Blackfin ghostshark, *Hydrolagus lemures*	8.0	6	100
Red cod, *Pseudophycis bachus*	7.8	14	100
Conger eel, *Conger* verreauxi	6.1	5	1
Shorttail torpedo ray, *Torpedo macneilli*	5.0	1	100
Gemfish, *Rexea solandri*	4.0	2	0
Silver dory, *Cyttus australis*	3.8	4	0
Sharpnose sevengill shark, *Heptranchias perlo*	3.0	1	0
Southern calamari, *Sepioteuthis australis*	3.0	3	0
Spiny boxfish, *Capropygia unistriata*	2.1	24	100
Common sawshark, *Pristiophorus cirratus*	2.0	1	100
Whiskery shark, *Furgaleus macki*	2.0	1	0
Blue mackerel, *Scomber australasicus*	1.8	9	100
Cocky gurnard, *Lepidotrigla modesta*	1.7	110	100
Leatherjackets, Monacanthidae spp	1.7	4	100

Sandpaper fish, *Paratrachichthys macleayi*	0.9	4	100
Rusty carpetshark, *Parascyllium ferrugineum*	0.8	1	100
Blue warehou, *Seriolella brama*	0.5	1	0

Table 2. Summaries of significance from Tweedie generalized linear mixed models explaining variation among the weights of total, retained and discarded species due to the fixed effect of 'codend configuration' comprising the half 94-mm T90, half 105-mm T90 and full 105-mm T90 coeends alternately fished with the same trawl in the Great Australian Bight over six fishing days in November 2022. The random effect of 'Days' was included in all models. Tl, total length

Variable	Codend configuration
Total catch	Ns
Retained catches	
Total	*
Deepwater flathead, *Neoplatycephalus conatus* ≥40 cm TL	*
Deepwater flathead <40 cm TL	***
Ocean jacket, *Nelusetta ayraudi*	Ns
Yellowspotted boarfish, *Paristiopterus gallipavo*	Ns (p = 0.08)
Red gurnard, *Chelidonichthys kumu*	Ns (p = 0.06)
Discarded catches	
Total	Ns
Latchet, *Pterygotrigla polyommata*	*
Australian burrfish, *Allomycterus pilatus*	Ns
Ringed toadfish, *Omegophora armilla*	*
Southern fiddler ray, *Trygonorrhina dumerilii*	Ns

*$p < 0.05$; **$p < 0.01$; ***$p < 0.001$; ns, not significant

Captions to figures

Fig. 1. Schematic diagram of the treatment codends, including the: traditional (a) half 94-mm T90, and new (b) half and (c) full 105-mm T90, and (d) the fishing vessel's full 85-mm T0 design; Ø, diameter; N = normal direction; T = transverse direction; SMO = stretched mesh opening. Standard errors are marked in parentheses.

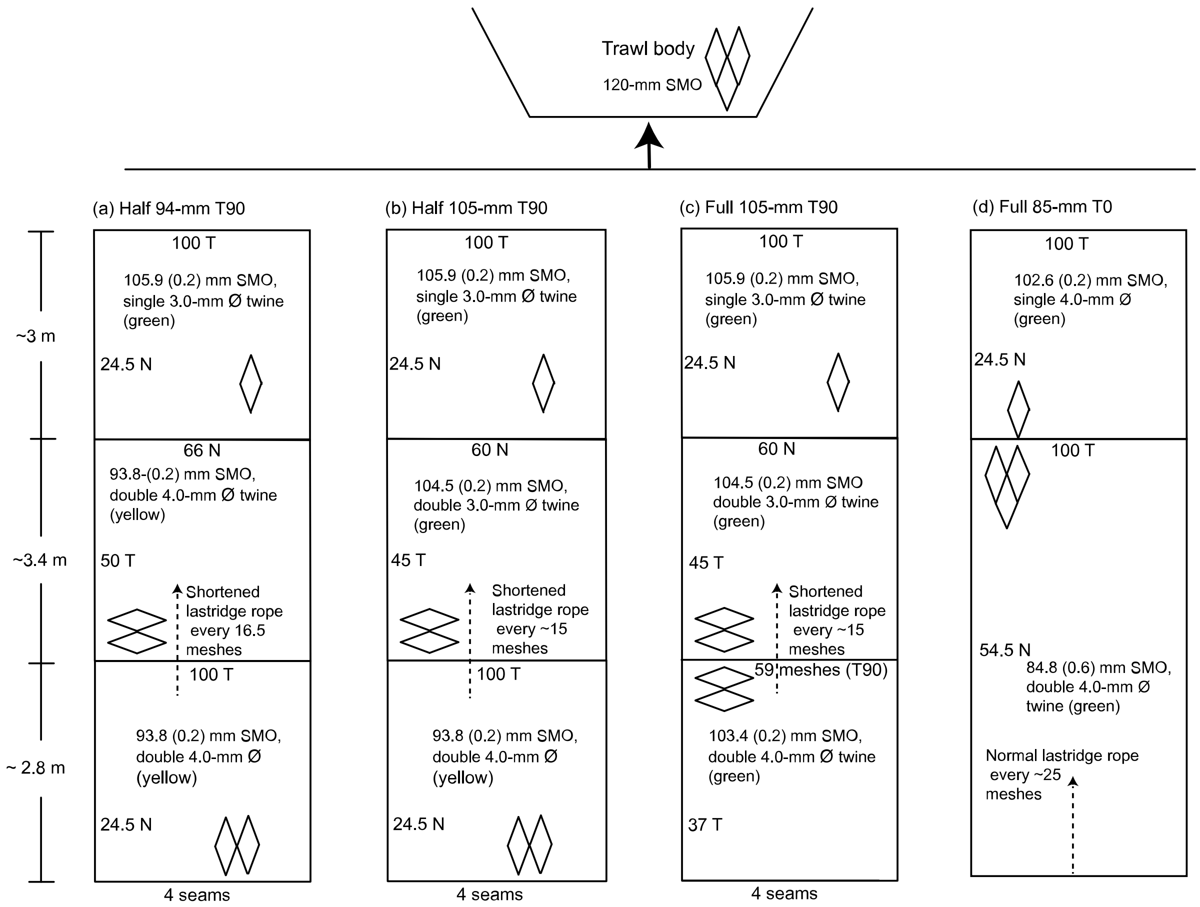
Fig. 2. Mean (±SE) weights (kg) ha^{-1} trawled between treatment codends for retained (a) total catch, deepwater flathead, *Neoplatycephalus conatus* (b) ≥40 cm and (c) < 40 cm total length (TL), (d) ocean jacket, *Nelusetta ayraudi*, (e) yellowspotted boarfish, *Paristiopterus gallipavo*, and (f) red gurnard, *Chelidonichthys kumu.* Letters above grey histograms for T90 codends only indicate significance or otherwise following any relevant false discovery rate pairwise comparisons ($p = 0.05$).

Fig. 3. Mean (±SE) weights (kg) ha^{-1} trawled between treatment codends for discarded (a) total catch, (b) latchet, *Pterygotrigla polyommata*, (c) Australian burrfish, *Allomycterus pilatus*, (d) ringed toadfish, *Omegophora armilla* and (e) southern fiddler ray, *Trygonorrhina dumerilii.* Letters above grey histograms for T90 codends only indicate significance or otherwise following any relevant false discovery rate pairwise comparisons ($p = 0.05$).

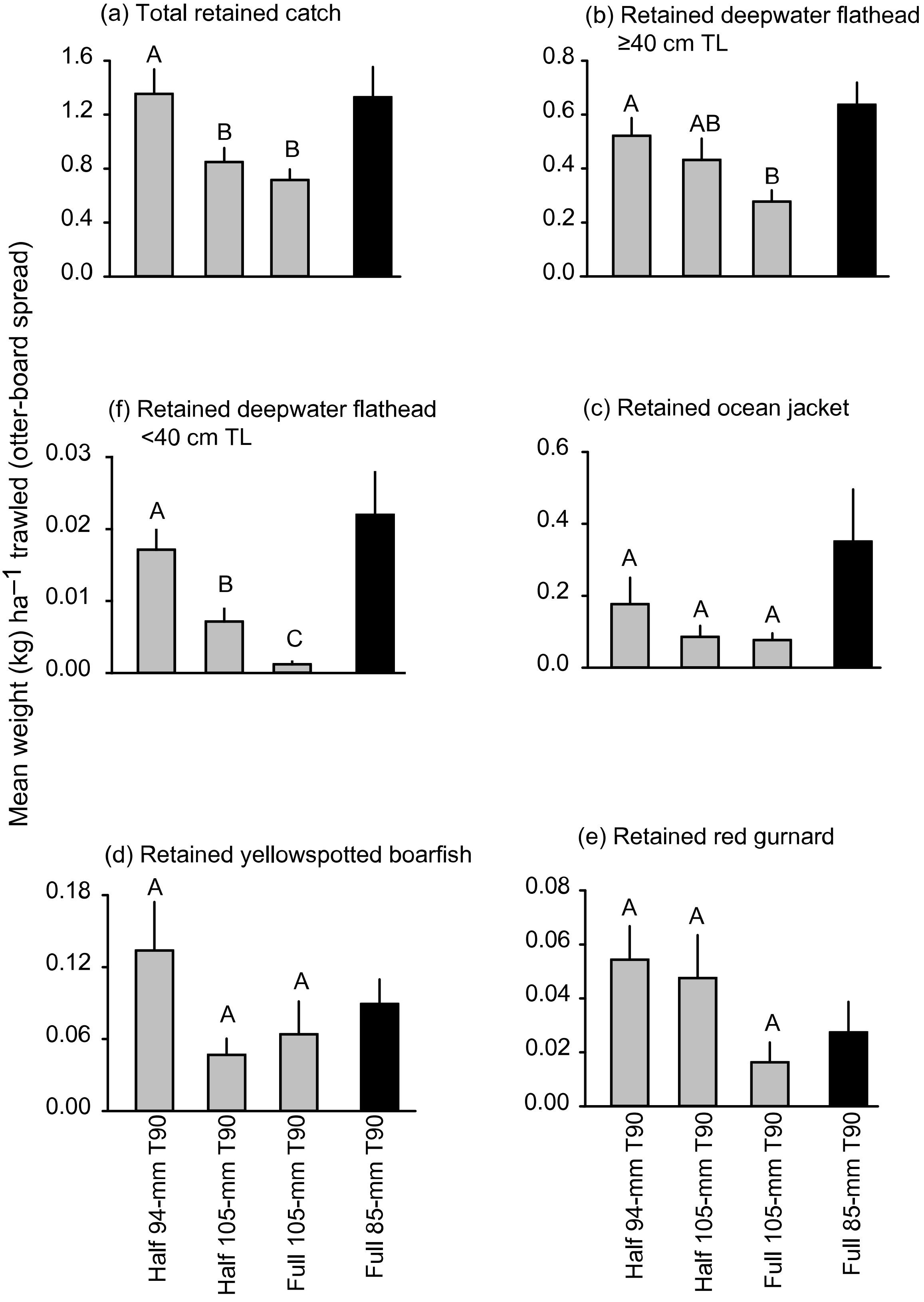
Fig. 4. Relative size-frequency plots for deepwater flathead, *Neoplatycephalus conatus* and latchet, *Pterygotrigla polyommata* caught in the (a and b) half 94-mm T90, (c and d) half 105-mm T90, (e and f) full 105-mm T90, and (g and h) full 85-mm T0 codends. The vertical dashed lines indicate the size (40 cm total length) of mature deepwater flathead.

Fig. 5. Cubic regression splines (solid lines) with 95% confidence intervals (grey bands) fitted to the proportions (black circles) of the combined catches of each total length (TL) class for deepwater flathead, *Neoplatycephalus conatus* and latchet, *Pterygotrigla polyommata* retained in the trawls with the (a and b) half 105-mm T90 codend and (c and d) full 105-mm T90 codends (from trawls with these codends and the half 94-mm T90), and with the (e and f) full 105-mm codend (from trawls with this design and the half 105-mm T90 codend). The 0.5 proportions retained (i.e. base line of equal efficiency between trawls) are marked with the narrow-dashed horizontal lines, and the probability of an effect of TL on relative selection (permutation test) is provided.

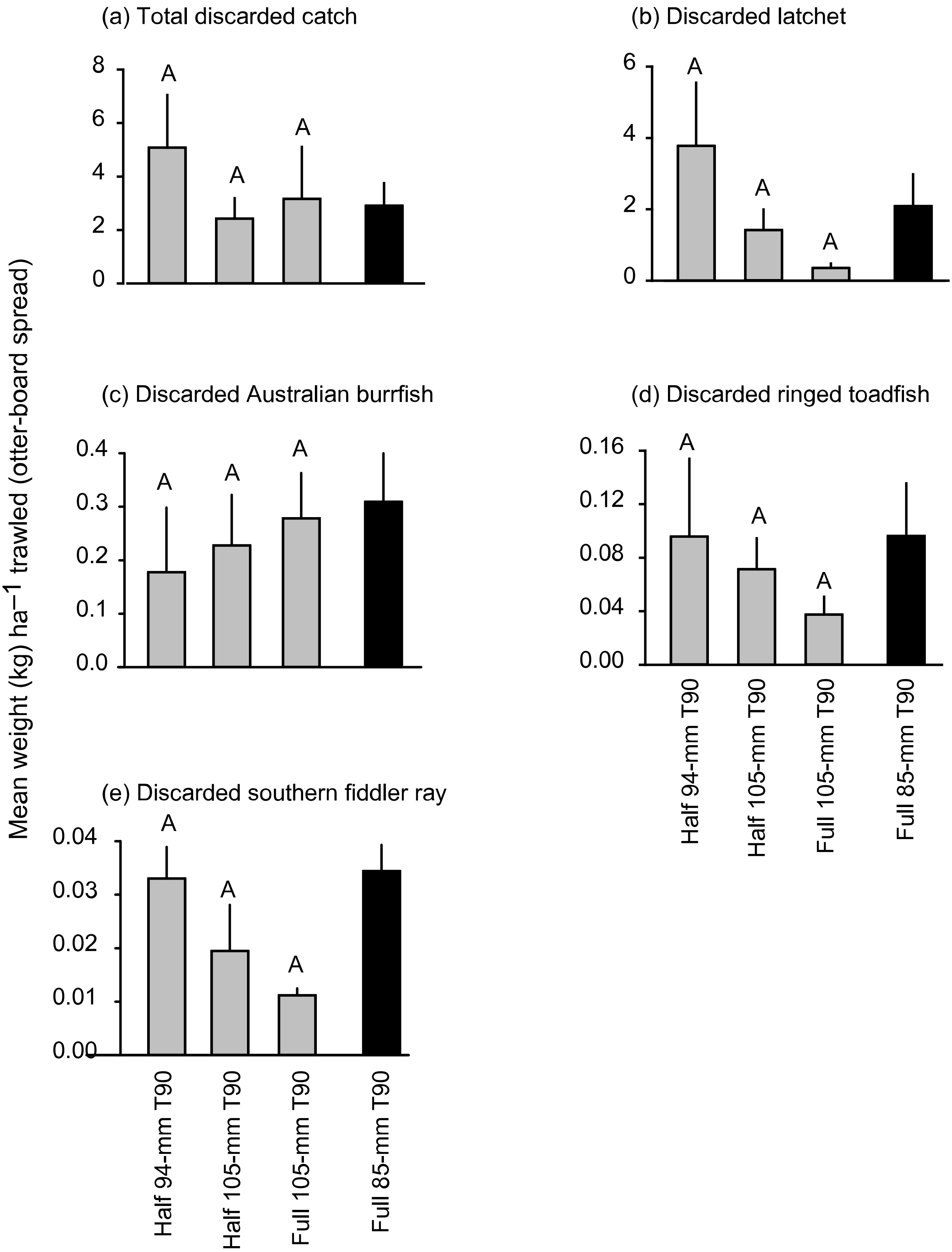
Fig. 6. Significant linear regressions of total length (TL) vs maximum width (MW), height (MH) and girth (MG) for deepwater flathead, *Neoplatycephalus conatus* sampled during the experiment.



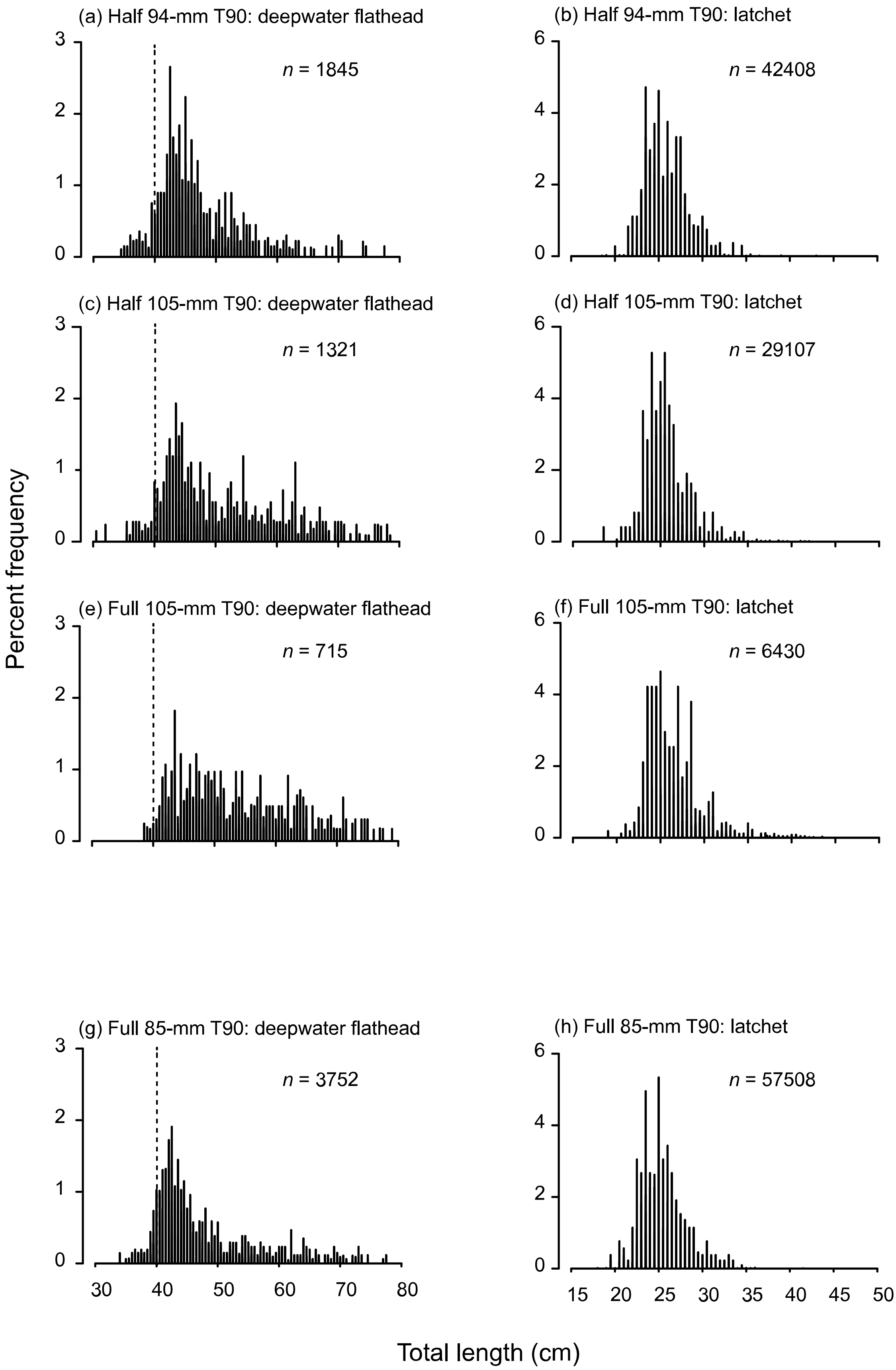
Trawl body
120-mm SMO
(a) Half 94-mm T90
(b) Half 105-mm T90
(c) Full 105-mm T90
(d) Full 85-mm T0
~3 m
~3.4 m
~ 2.8 m
100 T
105.9 (0.2) mm SMO, single 3.0-mm Ø twine (green)
24.5 N
66 N
93.8-(0.2) mm SMO, double 4.0-mm Ø twine (yellow)
50 T
Shortened lastridge rope every 16.5 meshes
100 T
93.8 (0.2) mm SMO, double 4.0-mm Ø (yellow)
24.5 N
4 seams
100 T
105.9 (0.2) mm SMO, single 3.0-mm Ø twine (green)
24.5 N
60 N
104.5 (0.2) mm SMO, double 3.0-mm Ø twine (green)
45 T
Shortened lastridge rope every ~15 meshes
100 T
93.8 (0.2) mm SMO, double 4.0-mm Ø (yellow)
24.5 N
4 seams
100 T
105.9 (0.2) mm SMO, single 3.0-mm Ø twine (green)
24.5 N
60 N
104.5 (0.2) mm SMO double 3.0-mm Ø twine (green)
45 T
Shortened lastridge rope every ~15 meshes
59 meshes (T90)
103.4 (0.2) mm SMO, double 4.0-mm Ø twine (green)
37 T
4 seams
100 T
102.6 (0.2) mm SMO, single 4.0-mm Ø (green)
24.5 N
100 T
54.5 N
84.8 (0.6) mm SMO, double 4.0-mm Ø twine (green)
Normal lastridge rope every ~25 meshes

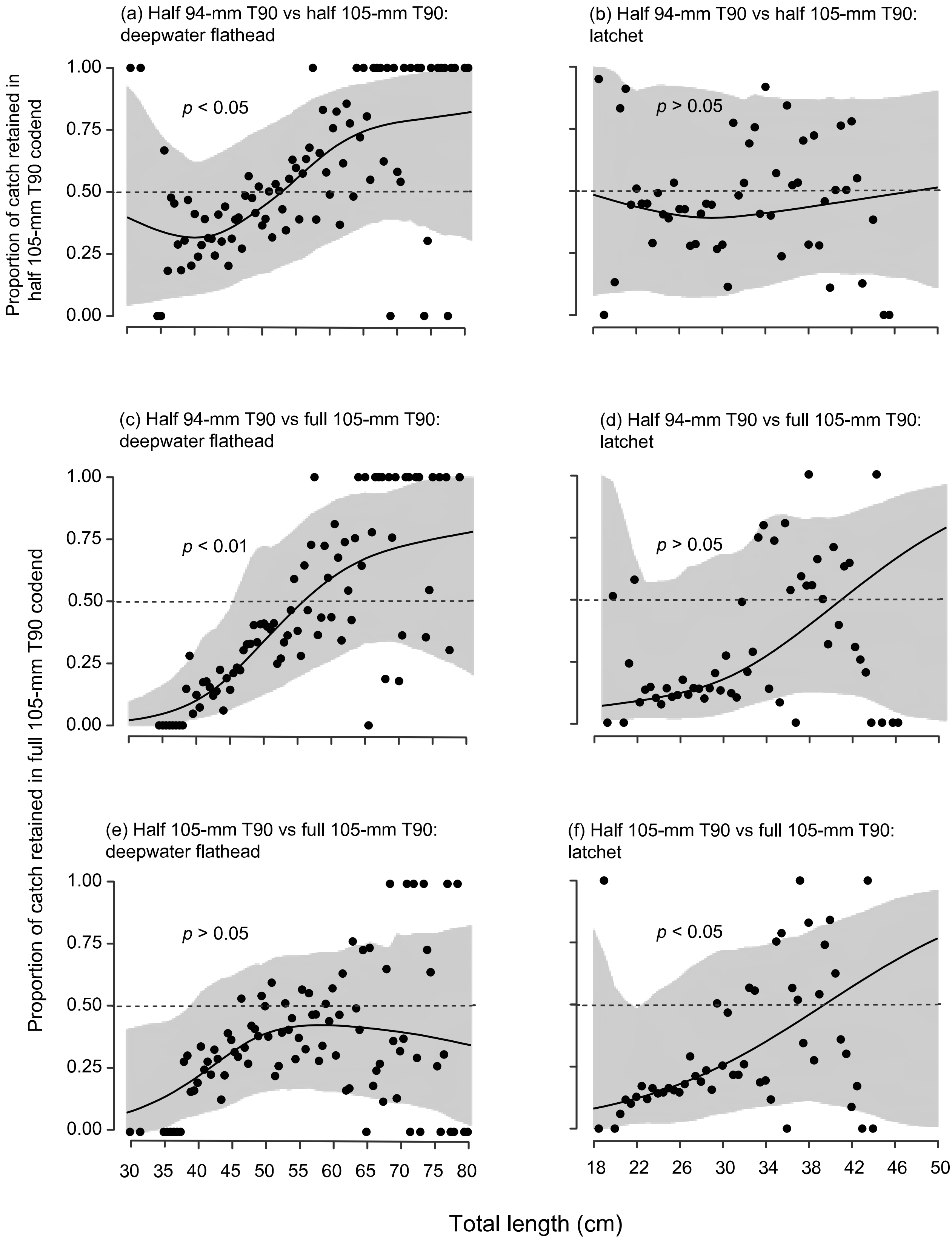


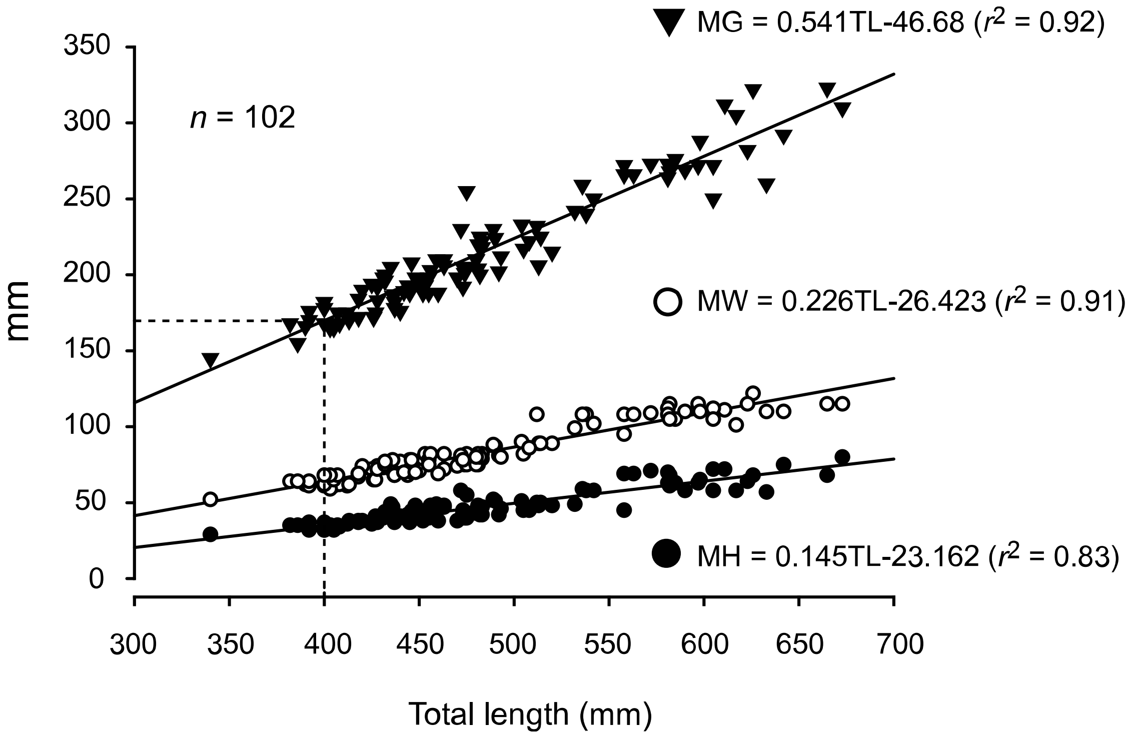
(a) Total retained catch
(b) Retained deepwater flathead ≥40 cm TL
(f) Retained deepwater flathead <40 cm TL
(c) Retained ocean jacket
(d) Retained yellowspotted boarfish
(e) Retained red gurnard
Mean weight (kg) ha^{-1} trawled (otter-board spread)
Half 94-mm T90
Half 105-mm T90
Full 105-mm T90
Full 85-mm T90



(a) Total discarded catch
(b) Discarded latchet
(c) Discarded Australian burrfish
(d) Discarded ringed toadfish
(e) Discarded southern fiddler ray
Mean weight (kg) ha⁻¹ trawled (otter-board spread)
A
8
6
4
2
0
0.4
0.3
0.2
0.1
0.0
0.16
0.12
0.08
0.04
0.00
0.03
0.02
0.01
Half 94-mm T90
Half 105-mm T90
Full 105-mm T90
Full 85-mm T90


(a) Half 94-mm T90: deepwater flathead
n = 1845
(b) Half 94-mm T90: latchet
n = 42408
(c) Half 105-mm T90: deepwater flathead
n = 1321
(d) Half 105-mm T90: latchet
n = 29107
(e) Full 105-mm T90: deepwater flathead
n = 715
(f) Full 105-mm T90: latchet
n = 6430
(g) Full 85-mm T90: deepwater flathead
n = 3752
(h) Full 85-mm T90: latchet
n = 57508
Percent frequency
Total length (cm)


(a) Half 94-mm T90 vs half 105-mm T90:
deepwater flathead
(b) Half 94-mm T90 vs half 105-mm T90:
latchet
(c) Half 94-mm T90 vs full 105-mm T90:
deepwater flathead
(d) Half 94-mm T90 vs full 105-mm T90:
latchet
(e) Half 105-mm T90 vs full 105-mm T90:
deepwater flathead
(f) Half 105-mm T90 vs full 105-mm T90:
latchet
Proportion of catch retained in
half 105-mm T90 codend
Proportion of catch retained in full 105-mm T90 codend
p < 0.05
p > 0.05
p < 0.01
p > 0.05
p > 0.05
p < 0.05
1.00
0.75
0.50
0.25
0.00
30 35 40 45 50 55 60 65 70 75 80
18 22 26 30 34 38 42 46 50
Total length (cm)


MG = 0.541TL-46.68 (r^2 = 0.92)
MW = 0.226TL-26.423 (r^2 = 0.91)
MH = 0.145TL-23.162 (r^2 = 0.83)
n = 102
mm
350
300
250
200
150
100
50
0
300
350
400
450
500
550
600
650
700
Total length (mm)

Appendix 10. Broadhurst, M.K., Knuckey, I.A. and Millar, R.B. 2023. Multi-specific effects of increased T90 mesh size and amount in an Australian fish trawl. Fron. Mar.Sci. 10:1196660. doi: 10.3389/fmars.2023.1196660

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Multi-specific effects of increasing T90 mesh size and amount in an Australian fish trawl

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Increases in the size and amount of meshes turned 90° ('T90') in an Australian fish-trawl codend were investigated to improve the size selection of deepwater flathead, *Neoplatycephalus conatus* and reduce discards. The conventional codend comprised 94-mm mesh throughout with normal orientation (diamond-shaped) in the posterior half but T90 in the anterior half ('half 94-mm T90' codend). Two new codends had 105-mm T90 mesh in the anterior section only ('half 105-mm T90') and throughout ('full 105-mm T90'). Both larger-meshed codends caught fewer immature deepwater flathead, but also lost some larger fish, especially the full 105-mm T90 codend, which had 80% more T90 meshes. The larger-meshed codends also allowed some discarded species to escape, but similarly affected other targets. Collected deepwater flathead morphological data support a T90 mesh size of ~100 mm in the anterior codend or ~94 mm throughout to maintain target sizes. However, irrespective of changes to codend meshes, owing to comparable inter-specific sizes and shapes, the discard percentage in this fishery will probably remain consistent at >75%, which is more than double the global average for fish trawls. Future efforts to improve selection in the fishery should consider modifications other than codend changes.

KEYWORDS
T90 codend, selectivity, bycatch and discards, fish trawl, lastridge rope

Introduction

Fish trawling is among the world's most common fishing methods, producing ~25 million t of seafood each year or ~25% of global marine production (Pérez Roda et al., 2019). Notwithstanding their importance, most fisheries involve multiple targets of varying morphologies and sizes, which can debase trawls to less-than-ideal selection and cause large subsets of catches to be discarded.

Various options are available for improving fish-trawl selectivity, although >70% of efforts have focused on the codend and historically by legislating appropriate diamond-mesh ('T0') sizes (Kennelly and Broadhurst, 2021). Efforts at improving codend selectivities have also included regulating other factors affecting lateral-mesh openings (regardless of mesh size), including twine diameters (Lowry and Robertson, 1996), codend circumferences (Reeves et al., 1992), or different mesh orientations (Kennelly and Broadhurst, 2021). The latter initially involved turning meshes 45° ('T45'; Robertson and Stewart, 1988) but more recently 90° ('T90') (Moderhak, 1997; Digre et al., 2010). Regardless of mesh type, shortened lastridge ropes have also been used to increase openings (Ingólfsson and Brinkhof, 2020).

Most work to improve fish-trawl selectivity has occurred in Europe (Kennelly and Broadhurst, 2021). Fewer efforts have been made in the Southern Hemisphere, including Australia, where there are 14 separately managed fish-trawl fisheries and ~135 licences, but with most in the south. Among the least selective fisheries is in the Great Australian Bight, where deepwater flathead, ***Neoplatycephalus conatus*** is a key target (Broadhurst et al., 2022). However, >300 species are discarded, mostly latchet, ***Pterygotrigla polyommata*** and stingarees, Urolophidae (van Putten et al., 2019).

Recently, to reduce unwanted bycatches and following overseas success (Ingólfsson and Brinkhof, 2020), Great Australian Bight operators have been using legislated codends comprising anterior sections (50% of codend) of T90 mesh made from conventional meshes [~94-mm stretched mesh opening (SMO)]. We assessed the utility of this commercially fished 'half 94-mm T90' codend against a traditional diamond-mesh design (Broadhurst et al., 2022). The T90 codend did not affect selection for the key target, deepwater flathead, and other retained species (ocean jacket, ***Nelusetta ayraud***; boarfish, ***Paristiopterus gallipavo***; or red gurnard, ***Chelidonichthys kumu***) or discarded species (latchets) (Broadhurst et al., 2022). These results were attributed to the mesh being too small, irrespective of orientation.

Deepwater flathead are regulated via a total catch (~1,200 t p.a), and while there is no size limit, they reach maturity at ~40-cm total length (TL), which is an appropriate minimum harvest size. The species is dorsally compressed, and theoretically, this body shape means that assuming their girth is less than the mesh perimeter, small fish should escape an appropriate-sized T90 mesh (Broadhurst et al., 2006). Owing to few fish trawlers in Australia, the range of available mesh sizes is limited and typically offered in 10-mm increments. Beyond 90- to 95-mm mesh, the next available material in similar twine diameters is ~105 mm.

Considering the above, the aims here were to compare the relative size and species selectivities of the half 94-mm T90 codend described by Broadhurst et al. (2022) and two new designs comprising 105-mm T90 mesh in the anterior section only and throughout. We sought to test the hypothesis that the new codends would retain deepwater flathead ≥40-cm TL and most ventrally compressed species, but allow small deepwater flathead and some unwanted catches to escape.

Materials and methods

The experiment was performed in the Great Australian Bight (33.12°S; 128.06°E to 33.27°S; 129.40°E) during 7 days in November 2022 using the FV "*Explorer S*" (35 m). The vessel had a conventional, single, two-seam trawl (Broadhurst et al., 2022). The posterior body (100 meshes in the transverse direction–T) was configured to alternately attach three extensions/codends (below). The vessel had a Scanmar trawl monitoring system to measure otter-board spread, a Lowrance global positioning system (GPS) to record distance and speed over the ground (SOG), and a Furuno echo sounder for depth.

Extensions and codends

Three four-panel extension/codend sections were constructed using up to four sheets of knotted polyethylene, braided netting. Each was measured for 20 replicate SMOs using a legislated purpose-built gauge comprising a weight (3 kg) attached below callipers. Twine diameters were recorded using vernier callipers. All extensions were made from a mean (± SE) SMO of 105.9 (0.18) mm (3-mm diameter–Ø twine) orientated as T0, measuring 24.5 meshes in the normal (N) direction and 100 T (Figure 1). Four lastridge ropes (24-mm Ø twisted polypropylene) were attached at the seams of the extension sections and measured the same stretched length (Figure 1).

A different four-panel codend was attached to each extension. The first ('half 94-mm T90') comprised an anterior section of 93.8 (± 0.17)-mm SMO (4-mm Ø double twine) turned 90° sewn across four panels for a total of 66 meshes around × 50 meshes deep (Figure 1A). Four 16-mm Ø Dynema lastridge ropes were attached at the junction of each panel and were 17% shorter than the stretched anterior codend length (Figure 1A). The T90 section was attached to a posterior T0 section measuring 24.5 N × 100 T and made from the same mesh as above, with lastridge ropes measuring the same length as the stretched meshes.

The second codend ('half 105-mm T90') had the same posterior section as the half 94-mm T90, but an anterior section made from four panels of 104.5 (± 0.19)-mm SMO T90 mesh (3-mm Ø double twine) totalling 60 meshes around × 45 meshes long (Figure 1B). Lastridge ropes were attached as above. The third codend ('full 105-mm T90') had the same T90 anterior section as the second, but the posterior section was also made from T90 mesh with an SMO of 103.4 (± 0.21) mm (4-mm Ø double twine) and was 59 meshes × 37 meshes long (i.e., 80% of the area of the anterior section; Figure 1C). Four 17% shorter lastridge ropes extended throughout both codend sections.

Experimental design

The codends were alternately attached to the trawl and deployed across the same locations over 7 days. Technical data were collected on the fished location, distance (km) and duration (h), otter-board spread (m), SOG (ms^{-1}), and depth (m). The latter three variables were logged every ~15 min to provide an average deployment^{-1}. After retrieval, the codend was emptied into an area with a measured volume, and the total catch weight was estimated. Retained catches were separated and boxed before weighing and counting. The total weight of discarded catch was estimated by subtracting the confirmed

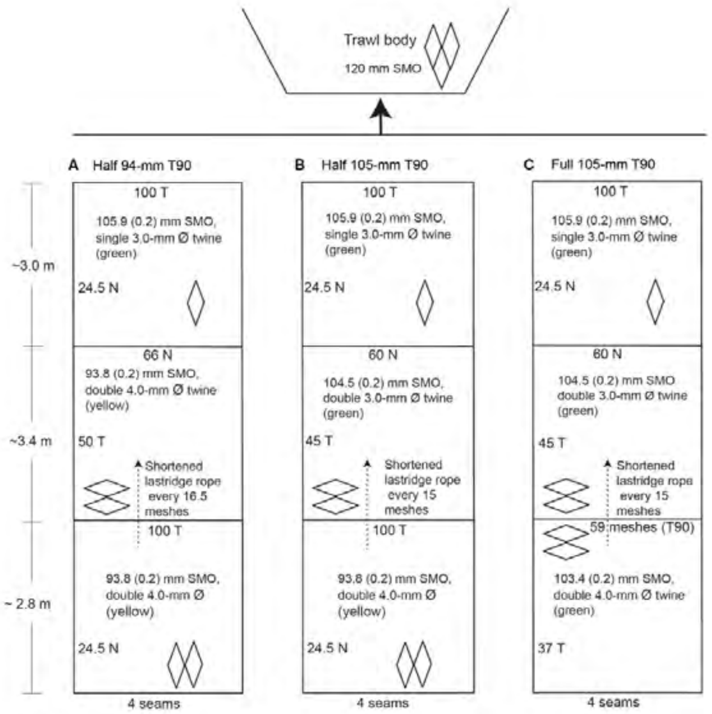

FIGURE 1
Schematic diagram of the treatment codends, including the traditional (A) half 94-mm T90 and new (B) half and (C) full 105-mm T90 codends. Ø, diameter; N, normal direction; T, transverse direction; SMO, stretched mesh opening. Standard errors in parentheses.

retained component from the total catch. Subsamples of discards were counted and weighed and extrapolated to the totals. Randomly selected subsamples of key species, but predominantly deepwater flathead and latchet (up to 130 deployment^{-1}) were measured to the nearest 0.5 cm (TL for fish and disc width for stingarees).

During three randomly selected deployments, 102 deepwater flathead were collected and immediately underwent measurement of their TLs and maximum heights (MHs), widths (MWs), and girths (MGs; all to the nearest 1 mm). The MH and MW were recorded using vernier callipers, while MG was taken by wrapping a length of polyamide twine (~1 mm Ø) around the thickest part of each fish and then measuring this.

Statistical analyses

Data describing otter-board spread were analysed using linear mixed models (LMM) comprising the fixed effects of 'codend', 'depth', and 'SOG'. The random term was 'day'. Backward elimination was used with non-significant fixed terms removed until the rest were significant at the 5% level using Wald tests. Standardized (ha^{-1} trawled; i.e., using otter-board spreads) weights of key species and combined catches were analysed with the Tweedie distribution (which incorporates zero inflation in non-negative numeric data and is applied on the log scale) and fitted using a generalized linear mixed model (GLMM) with codend and day as fixed and random effects, respectively.

Generalized additive modelling (GAM) was used to fit relative selectivity curves to the TL-frequency data for deepwater flathead and latchet (Supplementary Material). Length frequencies were first scaled up by deployment subsampling fractions to estimate total frequencies. Relative selectivity was assessed for each of the three possible pairings of the three gears (following Broadhurst et al., 2022). This catch-comparison analysis was implemented using the SELECT R package, which includes bootstrap functionality to incorporate between-haul variability (Millar et al., 2004; Millar, 2021). A permutation test was also used (10,000 resamples) to assess for statistical significance of codend configuration (Broadhurst et al., 2022).

The morphometric data for deepwater flathead were pooled across deployments and fitted against TL using linear regression. All analyses were performed using the R programming language.

Results

The three codends were fished during 20 deployments (six for the half 94-mm T90 codend and seven for each larger-meshed T90 codends) across comparable mean (± SE) durations (5.02 ± 0.04 h), depths (145.2 ± 4.4 m), and SOGs (1.6 ± 0.0 ms^{-1}). Otter-board spread (154.6 ± 1.0 m) was not affected by codend (LMM, $p > 0.05$) but did increase with depth (LMM, $p < 0.001$).

Thirty-nine tonnes, comprising >55 species, was caught, of which 8.4 t (>24 species) was retained and 30.9 t or 79% was discarded (Supplementary Table 1). Eight species (similar-sized) had sufficient quantities for analyses: latchet (98.5% discarded), deepwater flathead (none discarded), ocean jacket (44.9% discarded), southern fiddler ray, *Trygonorrhina dumerilii* (100% discarded), yellow-spotted boarfish (0% discarded), Australian burrfish, *Allomycterus pilatus* (100% discarded), red gurnard (0.3% discarded), and ringed toadfish, *Omegophora armilla* (100% discarded) (Supplementary Table 1).

Species selectivity

The GLMMs detected significant codend effects for the weights of retained total catches and deepwater flathead (both ≥40- and <40-cm TL) and discarded latchet and ringed toadfish ($p < 0.05$; Table 1). The weights of retained yellow-spotted boarfish and red gurnard had *p*-values of 0.08 and 0.06, respectively (Table 1). Most variables, except for southern fiddler rays (larger than all other species), showed the same trend of progressively lower weights in the half and then full 105-mm T90 codends than the conventional half 94-mm T90 codend (Table 1).

Size selectivity

Permutation tests detected significant TL effects for deepwater flathead in both 105-mm T90 codends *vs.* the half 94-mm T90 and for latchet in the full *vs.* half 105-mm T90 codends ($p < 0.05$; Figures 2A, C, F). Based on the fitted GAM cubic splines, deepwater flathead significance manifested as proportionally smaller fish (<~55-cm TL; albeit with considerable variability) escaping from the 105-mm T90 codends and especially the full design (Figures 2A, C). Among latchet, proportionally more individuals <~40-cm TL escaped the full than the half 105-mm T90 codend (Figures 2B, D, E).

Deepwater flathead morphology

Significant linear regressions were derived between TL ($n = 102$) and MG (MG = 0.541TL–46.680; $r^2 = 0.92$), MW (MW = 0.226TL–26.423; $r^2 = 0.91$), and MH (MH = 0.145TL–23.162; $r^2 = 0.83$) ($p < 0.001$). For deepwater flathead at 40-cm TL, the MG, MW and MH were ~170, 64, and 35 mm, respectively. The perimeter of a 105-mm SMO mesh (~210 mm) corresponded to a 47.5-mm TL individual.

Discussion

The data reiterate that slight increases in T90 mesh size and/or their amount in a codend can considerably affect species-specific size selection (Veiga-Malta et al., 2019; Cheng et al., 2020). Further, the changes to the codend were reasonably matched to deepwater flathead morphology, which supports maintained mesh openings throughout the new T90 codends, but with variability that appeared to increase with the amount of T90 meshes (i.e., the full 105-mm T90 had 80% more T90 meshes than the half 105-mm codend and allowed more fish across a greater size range to escape). Both larger-meshed T90 codends also

TABLE 1 Summaries of significance from Tweedie generalized linear mixed models for an effect of codend type on catch weights.

Variable	Codend	Half 94-mm T90	Half 105-mm T90	Full 105-mm T90
Total catch	ns	6.44 (2.05)	3.28 (0.78)	3.88 (1.96)
Retained catches				
Total	*	1.35 (0.18)	0.85 (0.10)	0.72 (0.08)
Deepwater flathead, *Neoplatycephalus conatus* ≥40-cm TL	*	0.52 (0.07)	0.43 (0.08)	0.28 (0.04)
Deepwater flathead <40-cm TL	***	0.02 (0.001)	0.007 (0.001)	0.001 (0.004)
Ocean jacket, *Nelusetta ayraud*	ns	0.18 (0.07)	0.09 (0.03)	0.08 (0.02)
Yellow-spotted boarfish, *Paristiopterus gallipavo*	ns (p = 0.08)	0.13 (0.04)	0.05 (0.01)	0.06 (0.03)
Red gurnard, *Chelidonichthys kumu*	ns (p = 0.06)	0.05 (0.01)	0.05 (0.01)	0.02 (0.01)
Discarded catches				
Total	ns	5.08 (1.96)	2.43 (0.76)	3.16 (1.94)
Latchet, *Pterygotrigla polyommata*	*	3.78 (1.77)	1.42 (0.58)	0.36 (0.12)
Australian burrfish, *Allomycterus pilatus*	ns	0.10 (0.06)	0.07 (0.02)	0.04 (0.01)
Ringed toadfish, *Omegophora armilla*	*	0.03 (0.005)	0.02 (0.008)	0.01 (0.001)
Southern fiddler ray, *Trygonorrhina dumerilii*	ns	0.18 (0.12)	0.22 (0.09)	0.28 (0.08)

Codend types comprised the half 94-mm T90, half 105-mm T90, and full 105-mm T90 (mean ± SE catches presented as ha^{-1} trawled) alternately fished with the same trawl during November 2022 in the Great Australian Bight. The random effect of 'day' was included in all models.
TL, total length.
*p < 0.05; ***p < 0.001; ns, not significant.

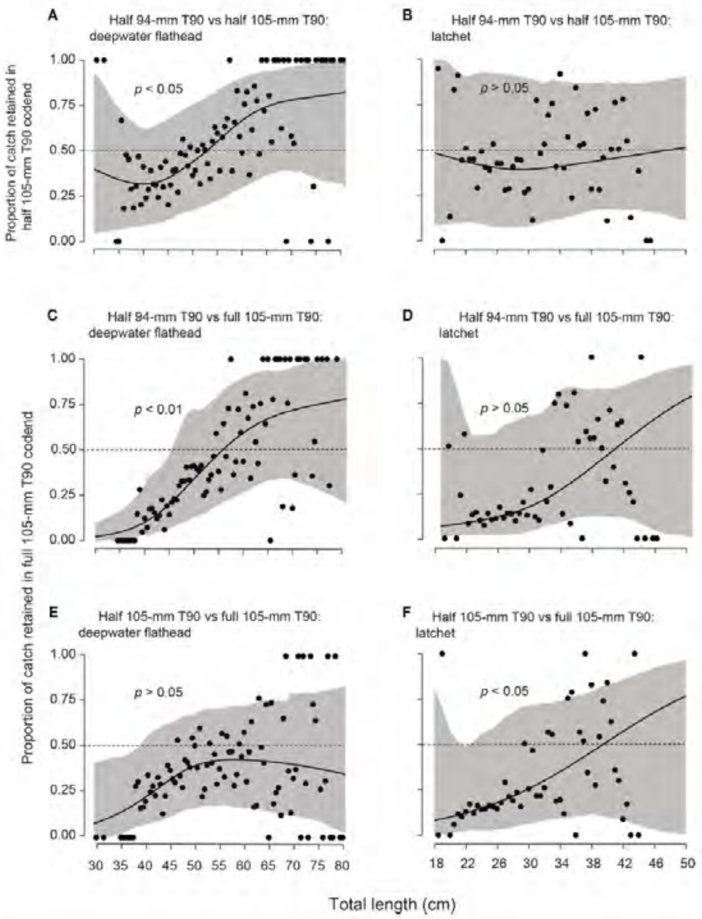

FIGURE 2
Cubic regression splines (solid lines) with 95% pointwise confidence intervals (grey bands) fitted to the proportions (black circles) of the combined catches of each total length (TL) class for deepwater flathead, *Neoplatycephalus conatus* and latchet, *Pterygotrigla polyommata* retained in the trawls with the (A, B) half 105-mm T90 and (C, D) full 105-mm T90 codends (from trawls with these codends and the half 94-mm T90), and the (E, F) full 105-mm codend (from trawls with this design and the half 105-mm T90 codend). The 0.5 proportions retained (i.e., baseline of equal efficiency between trawls) are marked with the narrow-dashed horizontal lines, and the p-values for effects of TL on relative selection (permutation test) are provided.

caught fewer discards, although as for other multi-species fisheries (e.g., Cheng et al., 2020; Robert et al., 2020), there were concomitantly lower catches of desired species, cumulatively reducing retained total catch. The utility of T90 here can be discussed by considering the morphology of deepwater flathead (and their fishing mortality prioritization) along with similar-sized retained and discarded species. Ultimately, this information might guide other selection refinements to regional trawls.

Any fish escaping through a mesh requires sufficient contact (often repeated) and cross-sectional dimensions smaller than mesh openings or, ultimately, the mesh perimeter (Broadhurst et al., 2006). Deepwater flathead have an MH-to-MW ratio of ~0.5, which matches the shape of a T90 mesh when held open by lastridge ropes (Broadhurst et al., 2006). Given the data collected here and assuming sufficient contact, conspecifics up to ~48-mm TL had a girth matching the perimeter of the 105-mm mesh, and so these and slightly larger fish (depending on orientation and compression) could have passed through. This estimated TL range is supported by the modelled relative selectivity curves, but clearly was not the only influence on the probability of deepwater flathead escaping, given the greater reductions in catches of fish <40-cm TL by the full 105-mm T90 codend. Presumably, increasing the amount of T90 meshes at an area where fish had the greatest probability of repeatedly encountering meshes (anterior to the catch) increased their escape (Robertson and Stewart, 1988; Reeves et al., 1992; Broadhurst et al., 2006).

The above results imply that a full T90 codend (or possibly the posterior section only) with a slightly smaller SMO might be appropriate for better regulating deepwater flathead size selection. We showed no effects on the size selection of deepwater flathead for the conventionally fished codend comprising 94-mm T90 mesh in the anterior section only (Broadhurst et al., 2022). This mesh corresponds to the girth of a 39-cm TL deepwater flathead, and so extending 94-mm T90 mesh throughout the codend might allow at least some conspecifics <40-cm TL to escape. Alternatively, increasing the T90 mesh to ~100 mm in the anterior section only—corresponding to a 42-cm TL deepwater flathead but assuming less probability of contact—might have some benefit.

Notwithstanding improved deepwater-flathead size selection due to increasing either the size or area of T90 mesh, other similar-sized species mean there will be cumulative reductions in not only discards but also some targets (Cheng et al., 2020; Robert et al., 2020). The discard species most affected by the larger-meshed T90 codends were latchet and ringed toadfish. Both fish are approximately fusiform, and like for deepwater flathead, smaller individuals were able to escape, especially from the full 105-mm T90 codend. Among the retained species, red gurnard is similarly fusiform, and while there was no significant reduction in their catches by the larger-meshed T90 codends, fewer were retained in the full 105-mm T90 codend. Based on morphometric data collected by Broadhurst et al. (2006), red gurnard with a girth of 210 mm (matching the 105-mm mesh) might measure ~38-cm TL, but individuals are retained down to <25-cm TL, and so there would be lost catches. In contrast, the retained ocean jacket and yellow-spotted boarfish are ventrally compressed, which might have limited many escaping, although mean catches were lower in the larger-meshed T90 codends.

It is clear in terms of discards, and notwithstanding relatively few replicate tows, that T90 mesh will not be an effective selective modification beyond allowing some small deepwater flathead to escape. Potentially, simpler codend modifications within existing configurations could have comparable utility. For example, although not as novel as T90 mesh, larger T0 mesh with or without shortened lastridge ropes might have sufficient benefits. Certainly, while complex industry-developed modifications should be encouraged, these should be compared against simpler options. An example of the problems of not following this protocol involves size-sorting grids in the Barents Sea (with 135-mm T0 codends), which were mandated to improve selection for cod, *Gadus morhua* during the late 1990s. However, Jørgensen et al. (2006) subsequently concluded that simply increasing the conventional T0 mesh to 155 mm (without a grid) provided the same benefits at a lower cost and complexity.

Regardless of the appropriate mesh size or shape to regulate deepwater flathead fishing mortality, ongoing work is clearly required because the discard rate recorded here is at least twice the global average for fish trawls (~30%; Pérez Roda et al., 2019). Beyond codend changes, other options include modifying the anterior trawl and excluding unwanted species by exploiting either tactile (e.g., alternative ground gears or separator panels) or visual (e.g., lights) stimuli (McHugh et al., 2017; Kennelly and Broadhurst, 2021). Such options may warrant investigation in the Great Australian Bight fishery, but like all efforts at improving trawl selectivity, this work will require close collaboration with, and support from, the industry to realise effective changes.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Author contributions

Conceptualization: MB, IK and RM; Data curation: MB; Formal analyses: RM; Funding acquisition: MB; Investigation: MB and IK; Methodology: MB and RM; Project administration: MB; Resources: MB; Software: MB and RM; Supervision: MB and IK; Validation: MB; Visualization: MB and RM; Roles/Writing – original draft: MB; Writing – review and editing: MB, IK and RM. All authors contributed to the article and approved the submitted version.

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Conflict of interest

Author IA is a Director of Fishwell Consulting.

The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fmars.2023.1196660/full#supplementary-material

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Supplementary material

Generalized additive modelling was used to fit relative size selectivity curves among the three codend comparisons. For example, for those tows involving the half 94-mm and 105-mm T90 codends, let n_l^{H94} and n_l^{H105} denote the number of length *l* fish caught. Then

$$p_l = \frac{n_l^{H105}}{n_l^{H94} + n_l^{H105}}$$

is the proportion caught in the H105 gear. The expected value of p_l was modelled on the logit scale using cubic regression splines of dimension three, denoted *s(l)*. That is:

$$E[p_l] = \frac{\exp(s(l))}{1 + \exp(s(l))}$$

The error distribution of p_l was specified to be quasi-binomial to incorporate overdispersion from subsampling. The GAMs were fitted in R using the gam function within the mgcv package (Wood, 2017). Confidence intervals were obtained using a 1000 iteration double bootstrap (Millar, 1993; Xu and Millar, 1993).

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Supplementary Table 1. List of species caught and % discarded during 20 deployments of three codends in the Great Australian Bight during November, 2022. Wt, weight. The size ranges (total length for fish and disc width for stingarees; all in cm) and numbers measured are given in parentheses.

Species	Wt (kg)	No.	% discarded (wt)
Latchet, *Pterygotrigla polyommata*	16197.7	78005	98.5 (18.5–45.5; 2046)
Wide stingaree, *Urolophus expansus*	10094.1	20852	100 (18.0–33.5; 291)
Deepwater flathead, *Neoplatycephalus conatus*	3508.5	3880	0 (30.5–80.5; 1807)
Southern fiddler ray, *Trygonorrhina dumerilii*	1997.4	504	100
Ocean jacket, *Nelusetta ayraudi*	1774.5	4944	44.9 (25.5–63.0; 618)
Gummy shark, *Mustelus antarcticus*	697.0	213	0
Yellowspotted boarfish, *Paristiopterus gallipavo*	686.4	448	0.1
Ornate angelshark, *Squatina tergocellata*	611.7	127	1.7
Gould's squid, *Nototodarus gouldi*	600.7	1060	0.2
Australian burrfish, *Allomycterus pilatus*	585.2	943	100
Greeneye dogfish, *Squalus chloroculus*	426.0	152	100
Red gurnard, *Chelidonichthys kumu*	345.0	525	0.3 (31.0–48.5; 110)
Bight redfish, *Centroberyx gerrardi*	270.5	198	0
Ringed toadfish, *Omegophora armilla*	180.3	593	100
Jackass morwong, *Nemadactylus macropterus*	171.9	649	87
Port Jackson shark, *Heterodontus portusjacksoni*	132.0	36	100
Knifejaw, *Oplegnathus woodwardi*	132.5	282	27.6
Smooth stingray, *Dasyatis brevicaudata*	118.0	18	100
Southern eagle ray, *Myliobatis tenuicaudatus*	67.0	4	100
Deepwater stargazer, *Kathetostoma nigrofasciatum*	65.5	234	100
Tusk, *Dannevigia tusca*	61.7	45	0
Barracouta, *Sphyraena novaehollandiae*	54.9	205	100
Spotted wobbegong, *Orectolobus maculatus*	50.0	1	0
Spikey dogfish, *Squalus megalops*	48.8	71	100
Blue morwong, *Nemadactylus valenciennesi*	46.0	11	0
Swallowtail, *Centroberyx lineatus*	45.6	283	100
John dory, *Zeus faber*	42.5	27	0
Banded wobbygong, *Orectolobus halei*	40.0	1	0
Common gurnard perch, *Neosebastes scorpaenoides*	39.8	103	100
Bighead gurnard perch, *Neosebastes pandus*	39.7	85	100
Blackspot boarfish, *Zanclistius elevatus*	36.1	108	24.9
Western shovelnose ray, *Aptychotrema vincentiana*	32.2	21	100
Melbourne skate, *Spiniraja whitleyi*	30.0	1	100
School shark, *Galeorhinus galeus*	23.0	27	0
Thetis fish, *Neosebastes thetidis*	19.3	55	100
Jack mackerel, *Trachurus declivis*	14.9	179	100
Harpuku, *Polyprion oxygeneios*	12.0	2	0
Whitebarred boxfish, *Anoplocapros lenticularis*	11.4	27	100
Fourspine leatherjacket, *Eubalichthys quadrispinis*	11.9	16	100
Bigeye ocean perch, *Helicolenus barathri*	8.4	18	100
Blackfin ghostshark, *Hydrolagus lemures*	8.0	6	100
Cuttlefish, Sepiidae	7.6	43	100
Blackspotted gurnard perch, *Neosebastes nigropunctatus*	7.0	11	0
Red cod, *Pseudophycis bachus*	6.5	10	100
Conger eel, *Conger verreauxi*	6.0	1	0
Shorttail torpedo ray, *Torpedo macneilli*	5.0	1	100
Mosaic leatherjacket, *Eubalichthys mosaicus*	3.8	3	100
Sharpnose sevengill shark, *Heptranchias perlo*	3.0	1	0
Southern calamari, *Sepioteuthis australis*	3.0	3	0
Spiny boxfish, *Capropygia unistriata*	1.4	14	100
Common sawshark, *Pristiophorus cirratus*	2.0	1	100
Whiskery shark, *Furgaleus macki*	2.0	1	0
Rusty carpetshark, *Parascyllium ferrugineum*	0.8	1	100
Southern rock lobster, *Jasus edwardsii*	0.8	1	100
Blue warehou, *Seriolella brama*	0.5	1	0

Appendix 11. Broadhurst, M.K. and Millar, R.B. 2024. No deleterious circumference effects for T90 codends in an Australian fish trawl targeting tiger flathead, *Platycephalus richardsoni*. Front. Mar. Sci. 11:1341890. doi:10.3389/fmars.2024.1341890

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No deleterious circumference effects for T90 codends in an Australian fish trawl targeting tiger flathead, *Platycephalus richardsoni*

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In an attempt to improve the selectivity of Australian fish trawls targeting tiger flathead, *Platycephalus richardsoni* (≥28 cm total length), the utility of four-seam codends with shortened lastridge ropes and comprising 71-mm meshes turned 90° (T90) hung at the narrowest and widest coherent circumferences was compared against a traditional 91-mm diamond-mesh (T0) codend. Significant effects of codend configuration were limited to an increase in the catches of another commercially important species, latchet, *Pterygotrigla polyommata*, by both T90 codends, and greater escape of some small tiger flathead from the wide 71-mm T90 codend than from the 91-mm T0 codend. Notwithstanding a need to investigate slightly larger T90 mesh sizes for the fishery, the data imply that unlike most codend configurations, circumference does not negatively affect selection in the stated designs and might not require future regulation.

KEYWORDS
bycatch, selectivity, T90, fish trawling, discard

Introduction

In Australia, the most economically important fish-trawl fishery is the southeastern "Commonwealth trawl sector" (CTS; valued at ~\$40 million), which involves ~30 vessels towing single-rigged trawls with a minimum legal stretched mesh opening (SMO) of 90 mm in the codend and retaining up to ~120 commercial species (~20 targeted), among which the platycephalid tiger flathead, *Platycephalus richarsoni*, dominates catches and is also one of the smallest-sized (Broadhurst et al., 2023). Vessels also discard non-commercial catches comprising >280 species and 40%–60% by weight of the total catches—an upper rate almost double the global average (Pérez Roda et al., 2019).

All targeted species are managed by quota, but tiger flathead is the only one with a legislated minimum legal total length (MLTL), currently 28 cm TL, which corresponds to a girth of ~130 mm, or the perimeter of a ~65-mm mesh (Hunt et al., 2014). While the girths of all 28-cm TL tiger flathead are considerably smaller than the perimeter of the legislated 90-mm mesh, it is well established that conventional diamond-shaped meshes (termed "T0") in trawl codends often have very narrow lateral mesh openings (Kennelly and Broadhurst, 2021). Key affecting factors include, but are not limited to, the twine diameter (Sala et al., 2007), codend circumference (Graham et al., 2009), towing speed (Sala et al., 2007), and catch weight (O'Neill et al., 2008). Interactions between factors typically mean T0 codend meshes open to ~0.25–0.35× the SMO and, therefore, have to be much larger than the girths of fish at MLTL to maintain appropriate selectivity (Graham et al., 2009).

To reduce lateral mesh openings in 90-mm SMO codends and retain legal-sized tiger flathead, CTS trawlers legally use up to 8-mm-diameter (Ø) single or 6-mm Ø double braided twine. However, these conventional configurations likely produce considerable variability in mesh openings (Kennelly and Broadhurst, 2021). Two simple methods of maintaining consistent lateral mesh openings in codends (to approach 0.5× the SMO) are to turn some or all meshes either 45° ("T45" or square mesh; Sala et al., 2008) or, more recently, 90° (T90; Wienbeck et al., 2011), and/or include shortened ropes ("lastridge" ropes; Ingólfsson and Brinkhof, 2020) down the sides of a codend to reduce tension on the netting. Notwithstanding considerable species-specific variability, slightly smaller sizes of T90 mesh in codends constructed with four seams and shortened lastridge ropes can select fish over narrower size ranges than larger, conventional T0 meshes (without these design modifications; Kennelly and Broadhurst, 2021).

Despite improved consistency in lateral mesh openings, similar to T0 codends, there will be influencing factors affecting T90. In particular, there remains limited information on the effects of circumference on T90 codend performances, although increasing circumference reduces the selection of T0 codends, and less so for T45 codends (Kennelly and Broadhurst, 2021). The relatively few studies assessing T90 codends have tested treatments across various circumferences, including at 50% (Wienbeck et al., 2011), 60% (Einarsson et al., 2021), 66% (Digre et al., 2010; Cheng et al., 2020; Robert et al., 2020; Broadhurst et al., 2022), 80% (Kopp et al., 2018), 85% (Ingólfsson and Brinkhof, 2020), and 100% (Lomeli et al., 2017; Sola and Maynou, 2018) of the stretched circumference of the conventional T0 codends. Most of these T90 codends did not have shortened lastridge ropes (but see Einarsson et al., 2021; Broadhurst et al., 2022).

Greater clarity on the effects of the circumference of T90 codends is required considering there are few studies and at least some species-specific effects. For example, doubling the circumference of T90 codends without lastridge ropes decreased size selection for Atlantic cod, *Gadus morhua* (Wienbeck et al., 2011; Veiga-Malta et al., 2019), but had no effect on bogue, *Boop boops* (Ilkyaz et al., 2017). Given the above, here we sought to test the hypothesis of no differences in the relative size and species selection of a conventional T0 codend and two new smaller-meshed, four-seam T90 codends at two circumferences and with shortened lastridge ropes when targeting tiger flathead in the CTS. Specifically, the T0 codend comprised conventional ~91-mm SMO, while the T90 codends were made from ~71-mm SMO—chosen to approach the approximate girth of 28-cm TL tiger flathead—and were constructed with circumferences of ~66 and 100% that of the stretched T0 codend.

Materials and methods

The experiment was done off Ulladulla, New South Wales (37.35°S; 150.46°E) between 12 April and 1 August 2023 using the 23-m "FV Francesca". Onboard equipment included a Notus trawl-monitoring system to measure otter-board spread and a Lowrance global positioning system (GPS) to record the distance travelled and speed over the ground (SOG). The Francesca fished a conventional two-seam trawl body (42-m headline length) made from knotted, braided polyethylene (PE) twine, comprising 104- to 146-mm SMOs throughout and attached to 24-m bridles, 274-m sweeps (20-mm Ø rope), and 600-kg steel otter boards (Broadhurst et al., 2023). A lengthener (extension) made from nominal 104-mm T0 mesh (3.5-mm Ø twine) and measuring 100 meshes in the normal direction (N) and 130 meshes in the transverse direction (T) was attached posterior to the trawl body to facilitate swapping three codends (below; Figure 1). The lengthener had two 6-m lengths of 16-mm Ø braided polyamide ropes sewn along the side seams at the same length as the stretched meshes to distribute the load of the four shortened lastridge ropes on the T90 codends described below.

Codends

Three new, short lengthener and codend sections were constructed from green, braided (PE) netting (Figure 1). During construction, all netting was measured for 20 replicate SMOs to the nearest 0.5 mm using a purpose-built gauge and twine Ø (nearest 0.1 mm) using Vernier calipers. The short lengtheners were identical and made from a mean SMO (± SE) of 90.6 (0.2)-mm T0 mesh (3.4 ± 0.1-mm twine Ø) measuring 30 N × 130 T and were attached to one of three codends that differed in their mesh sizes, twine diameters, and/or circumferences (Figures 1A-C).

The first codend design was the conventional "91-mm T0" and was made from 90.6 (0.2)-mm mesh (6.2 ± 0.1-mm Ø twine) and measured 30 N × 100 T (Figure 1A). The second and third codends comprised the same 70.9 (0.2)-mm mesh made from 3.6 (0.1)-mm-diameter twine turned 90° and were constructed from four panels with 16-mm Ø Dynema® lastridge ropes attached at the junction of each (17% shorter; Broadhurst et al., 2022) (Figures 1B, C). Both codends measured 49 meshes long, but one ("narrow 71-mm T90") had 86 meshes in circumference (i.e., 66% of the 91-mm T0 codend circumference; Figure 1B), and the other ("wide 71-mm T90") measured 130 meshes in circumference (i.e., 100% of the 91-mm T0 codend circumference; Figure 1C). For the T90 codends, the lastridge ropes were paired into two bridles at the short lengthener on each side and then shackled to the ropes running along the main

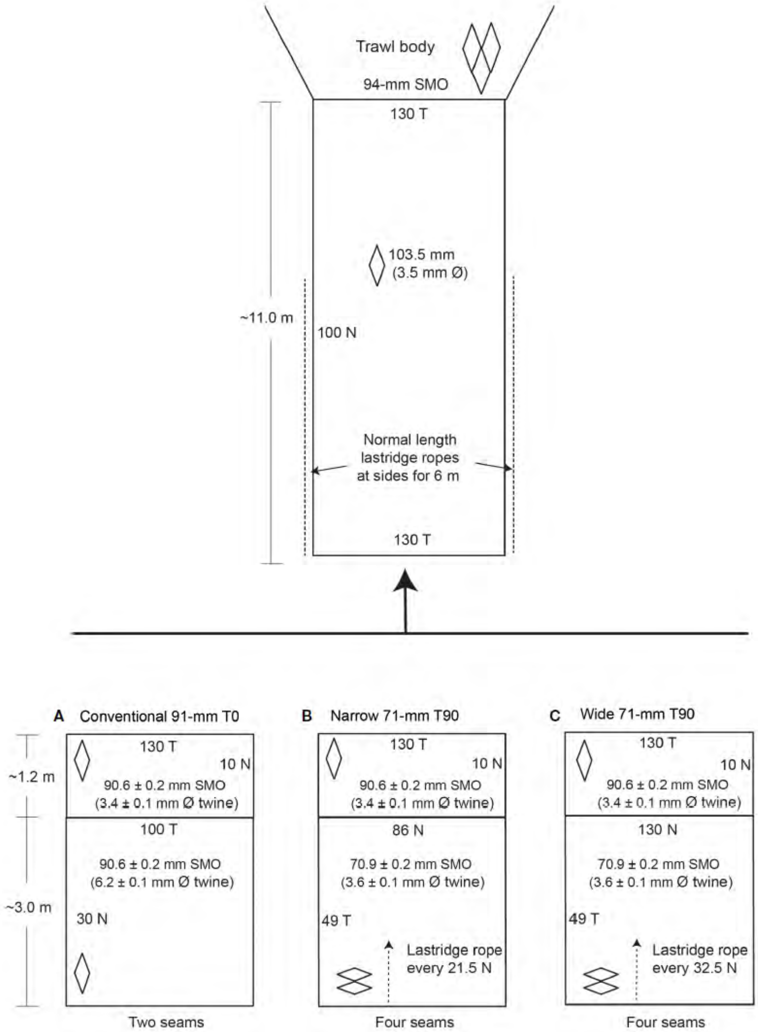

FIGURE 1
Diagram of the main trawl lengthener and short lengtheners attached to the **(A)** conventional 91-mm T0 codend, and **(B)** narrow and **(C)** wide 71-mm T90 codends. SMO, stretched mesh opening; T, transversals; N, normals; Ø, diameter.

lengthener when the codends were secured by lacing lengtheners together with 4-mm Ø polyamide rope.

Experimental design and data collected

The three codends were alternately fished on the trawl in an attempted blocked design mostly comprising three deployments with two codends tested on each fishing day, and with two replicates of each codend every 2 days. Prior to deployment, the tested codend was attached, and the trawl was deployed across fishing grounds randomly selected from available options on each day according to weather conditions and encompassing the same depth ranges across replicate treatments.

Technical data collected included otter-board spread, start and end times of the deployments (otter boards on and off the bottom), total distance trawled, and SOG. At the end of each deployment, catches were emptied onto a confined area of the deck with a known volume and the total weight was estimated. Individuals of target and by-product species were separated and placed into 55-L boxes before weighing and counting. The remaining bycatch, including individuals of commercially important species smaller than the desired sizes, were sorted, and abundant non-commercial discards were counted and weighed. Subsamples of key species were measured to the nearest 0.5 cm TL.

Data analyses

The hypothesis of no differences in SMOs and twine Øs between codends was analyzed using a linear model (LM). Data describing otter-board spreads were analyzed using a linear mixed model (LMM) comprising the fixed effects of "codend", "depth", and "SOG", and the random effect of "days". Depth and standardized (ha^{-1} trawled) log-transformed catch variables were also analyzed with LMMs when data were >0 (log-transformed to act multiplicatively), or if the data were 0, generalized linear mixed models (GLMMs) with the Tweedie distribution were used. These models had codend and days as fixed and random effects, respectively. Any significant effects between the three codends were explored using false discovery rate (FDR) pairwise tests.

Generalized additive modeling (GAM) was used to fit relative size selectivity curves to scaled-up data (by deployment subsampling) for tiger flathead and abundant discarded species among each of the three possible pairings of the codends (Supplementary Material). This catch-comparison analysis was implemented using the SELECT R package, which includes bootstrap functionality to incorporate between-haul variability (Millar, 2021). A permutation test was used (1,000 resamples) to test for no TL effects due to codend configuration (i.e., relative selectivity is the same for all TLs; Broadhurst et al., 2022). Analyses were done in R (R Core Team, 2021).

Results

The SMOs and twine Øs were significantly different between codends, with the 91-mm T0 codend having larger meshes (mean ± SE of 90.6 ± 0.2) and twine Øs (6.2 ± 0.1) than the T90 codends (LM and FDR, $p < 0.05$), which were identical (pooled means of 70.9 ± 0.2 and 3.6 ± 0.1 mm) (LM, FDR, $p > 0.05$). During 14 days at sea, we completed 12, 13, and 14 replicate deployments of the 91-mm T0, and narrow and wide 71-mm T90 codends over durations of 0.91 to 4.55 h and SOGs of 1.5 to 2.0 ms^{-1}. There was no significant difference in otter-board spreads (112.9 ± 2.2 m) of the trawl when attached to the three codends or the depths (102.2 ± 6.9 m) and areas (161.6 ± 10.4 ha) trawled (LMM, $p > 0.05$). Nevertheless, catches were standardized to ha^{-1} trawled. Otter-board spread was significantly and positively associated with depth and SOG (LMM, $p < 0.01$).

The total catch was 28 t, of which 18.5 t (66%) was discarded, including ~7 t of elasmobranchs (Supplementary Table 1). More than 110 species were caught, but 13 comprised ~70% of the total, and these formed the analyses of species selection (Table 1).

Species selectivity

Significant codend effects were limited to the numbers and weights of retained latchets ha^{-1}, which, while caught in low numbers (i.e., in only 2 hauls of the T0, but 13 hauls of the T90 codends), had mean catches that were similarly greater in the narrow (0.06 ± 0.04 and 0.07 ± 0.04 ha^{-1}) and wide 71-mm T90 codends (0.08 ± 0.03 and 0.02 ± 0.01 ha^{-1}) than in the 91-mm T0 codend (0.0003 ± 0.0002 and 0.001 ± 0.0008 ha^{-1}) (LMM and FDR $p < 0.05$, Table 1, Supplementary Material). Although not significant, the *p*-values for the number of retained and weights of discarded tiger flathead were 0.06 and 0.09, and with a trend of more retained in the narrow 71-mm T90 codend than the other two designs (Table 1, Supplementary Material). Similar non-significant differences were observed for several other variables, including the total retained and discarded weights (Table 1).

Relative size selectivity

Sufficient size data were collected for tiger flathead and the abundant discard, round-snouted gurnard, *Lepidotrigla mulhall* (but not for latchet), to permit analyses. Significant TL effects were limited to tiger flathead caught in the wide 71-mm T90 vs. the 91-mm T0, whereby the GAM cubic spline showed the former codend retained proportionally fewer small fish and especially those <30 cm TL (permutation test, $p < 0.05$; Figure 2A). In contrast, the proportions of tiger flathead retained in the other two codend pairings and for round-snouted gurnard across all three paired comparisons remained consistent for all TLs (Figures 2B-F).

Discussion

The data contribute toward the few studies exploring the effects of T90 codend circumference (Wienbeck et al., 2011; Veiga-Malta et al., 2019) and address the dearth of information describing any such effects in the presence of shortened lastridge ropes—which appear to help homogenize selection. While the tested 71-mm SMO minimally impacted tiger flathead catches, both T90 codends similarly retained more of another small by-product species, and without significantly affecting the weight of total discards. These findings support future directions for assessing generic T90 codends in fish trawls, and for maximizing their selective performances in the CTS.

It is difficult to rationalize mesh size and/or configuration in a multispecies fishery with different sizes and/or morphologies of fish because optimizing selection for one species invariably negatively or positively affects others (Broadhurst et al., 2023). Here, we aimed to improve size selection for tiger flathead using 71-mm mesh (~20% smaller than the conventional 90-mm mesh) that was slightly larger than the approximate girth of fish with 28 cm TL. However, this mesh was probably too small, although the almost significant differences for numbers and weights (p = 0.06 and 0.09) and significant TL effects between the wide 71-mm T90 and conventional 91-mm T0 codends imply some small tiger flathead were able to escape more easily. Perhaps of greater importance is that, because there were no significant differences in any size or species selection between T90 designs, unlike for T0 codends (Graham et al., 2009), any increase in T90 mesh size could occur

TABLE 1 Summaries of significance from mixed-effects models testing for the effects of "codend" (91-mm T0 vs. narrow and wide 71-mm T90) on the numbers and weights of key retained and discarded species/groups, and mean catches ($\pm$ SE).

Variable	Codend	91-mm T0	Narrow 71-mm T90	Wide 71-mm T90
Retained catches				
Total wt	Ns	1.71 (0.42)	1.85 (0.35)	1.36 (0.18)
Wt of tiger flathead, *Platycephalus richardsoni* ≥28 cm TL	Ns	0.20 (0.05)	0.47 (0.08)	0.29 (0.07)
No. of tiger flathead	p = 0.06	0.50 (0.15)	1.18 (0.21)	0.70 (0.20)
Wt of eastern angel shark, *Squatina albipunctata*	Ns	0.16 (0.12)	0.22 (0.08)	0.11 (0.03)
No. of eastern angel shark	Ns	0.08 (0.07)	0.04 (0.01)	0.02 (0.01)
Wt of redfish, *Centroberyx affinis*	Ns	0.07 (0.04)	0.19 (0.07)	0.08 (0.04)
No. of redfish	Ns	0.40 (0.23)	1.36 (0.66)	0.48 (0.29)
Wt of eastern school whiting, *Sillago flindersi*	Ns	0.21 (0.11)	0.17 (0.09)	0.06 (0.03)
No. of eastern school whiting	Ns	3.57 (1.81)	2.22 (1.18)	0.89 (0.43)
Wt of red gurnard, *Chelidonichthys kumu*	Ns	0.03 (0.02)	0.07 (0.02)	0.08 (0.04)
No. of red gurnard	Ns	0.05 (0.02)	0.13 (0.03)	0.12 (0.05)
Wt of latchet, *Pterygotrigla polyommata*	**	0.00 (0.00)	0.06 (0.04)	0.08 (0.03)
No. of latchet	**	0.00 (0.00)	0.07 (0.04)	0.02 (0.01)
Wt of Gould's squid, *Nototodarus gouldi*	Ns	0.01 (0.01)	0.02 (0.01)	0.01 (0.00)
No. of Gould's squid	Ns	0.02 (0.01)	0.04 (0.02)	0.02 (0.01)
Wt of John dory, *Zeus faber*	Ns	0.01 (0.01)	0.03 (0.01)	0.03 (0.01)
No. of John dory	Ns	0.03 (0.01)	0.04 (0.01)	0.02 (0.01)
Discarded catches				
Total wt	Ns	2.63 (0.74)	4.79 (1.74)	1.81 (0.33)
Wt of round-snouted gurnard, *Lepidotrigla mulhalli*	Ns	0.18 (0.07)	1.19 (0.56)	0.38 (0.12)
No. of round-snouted gurnard	Ns	3.50 (1.15)	22.48 (10.48)	6.92 (2.16)
Wt of southern fiddler ray, *Trygonorrhina dumerilii*	Ns	0.51 (0.22)	0.75 (0.27)	0.52 (0.25)
No. of southern fiddler ray	Ns	0.17 (0.07)	0.28 (0.08)	0.22 (0.12)
Wt of tiger flathead <28 cm TL	p = 0.09	0.02 (0.01)	0.03 (0.01)	0.01 (0.00)
No. of tiger flathead <28 cm TL	Ns	0.17 (0.07)	0.26 (0.07)	0.10 (0.04)
Wt of redfish	Ns	0.01 (0.00)	0.18 (0.16)	0.02 (0.01)
No. of redfish	Ns	0.10 (0.05)	0.45 (0.22)	0.18 (0.10)
Wt of velvet leatherjacket, *Meuschenia scaber*	Ns	0.07 (0.05)	0.02 (0.01)	0.02 (0.01)
No. of velvet leatherjacket	Ns	0.17 (0.07)	0.17 (0.06)	0.16 (0.07)
Wt of Australian burrfish, *Allomycterus pilatus*	Ns	0.04 (0.01)	0.03 (0.01)	0.03 (0.01)
No. of Australian burrfish	Ns	0.08 (0.03)	0.07 (0.02)	0.07 (0.02)

**p < 0.001; Ns, not significant; TL, total length.
The random effect of "days" was included in all models.

with flexibility in codend circumference (i.e., 66%–100% of a conventional T0 design).

Normally, increasing codend circumference in the absence of lastridge ropes negatively affects selection in T0 codends (Graham et al., 2009) and at least some T45 (Broadhurst and Millar, 2009) and T90 (Wienbeck et al., 2011) designs. These effects occur because excessive circumferences cause meshes to convolute under strain, which blocks some openings. The catch and size data imply no such effects here. Rather, the wide 71-mm T90 codend (but not the narrow 71-mm T90) had slightly improved selection over the 91-mm T0. Possibly, because the short lastridge ropes supported the weight of the codend during fishing, the T90 meshes did not

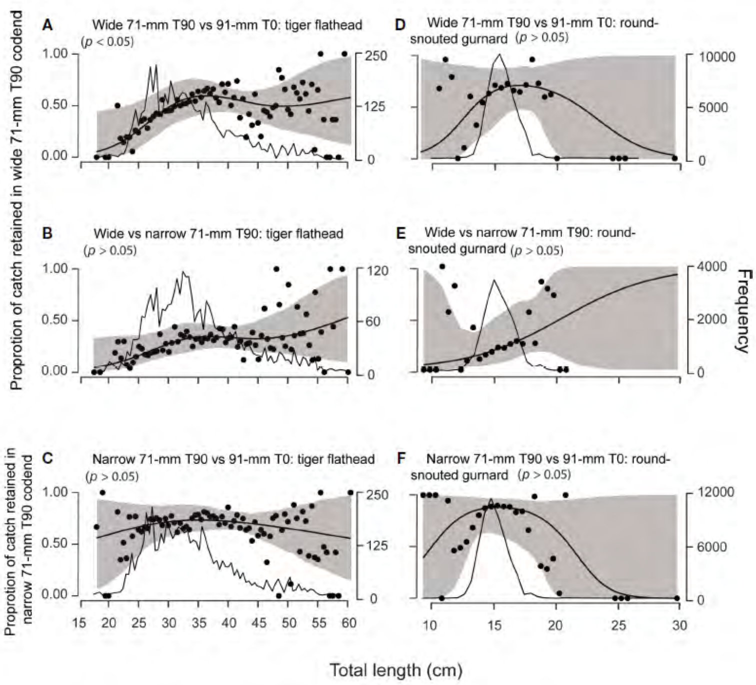

FIGURE 2
Cubic regression splines (solid lines) with 95% confidence intervals (gray) fitted to the proportions (black circles) of the combined catches (represented by continuous frequency curves) of each total length for tiger flathead, *Platycephalus richardsoni*, and round-snouted gurnard, *Lepidotrigla mulhalli*, from the **(A, D)** 91-mm T0 and wide 71-mm T90 codends that were retained in the latter, **(B, E)** narrow and wide 71-mm T90 codends that were retained in the latter, and **(C, F)** 91-mm T0 and narrow 71-mm T90 codends that were retained in the latter. The *p*-values (permutation test) for an effect of TL on relative selection are provided.

excessively convolute, and the wide 71-mm T90 codend simply provided more openings for small tiger flathead to escape.

Notwithstanding a similar general trend of relatively less total and discarded catches in the wide 71-mm T90 codend than the other designs, significance did not extend to any other variables, including catches of latchet, which was the only other species affected by the codends. Although quite low numbers were caught, and this species is of less importance than many others, latchet catches were similarly and significantly greater in both T90 codends, which may be explained by their small size and morphology. Latchet are thinner and more fusiform than tiger flathead, and many small individuals probably squeezed through the 91-mm mesh. Regardless of codend circumference, the smaller 71-mm mesh appeared more appropriate than the conventional 91 mm for latchet.

The consistent increases in catches of one by-product species, combined with evidence of a slight improvement in size selection for tiger fathead and no significant increase in discards by the 71-mm T90 codends, warrant additional work to examine similar designs with meshes between ~75 and 80 mm SMO. It might also be possible to use similar-sized T0 mesh and simply attach lastridge ropes. Greater clarity on the effects of shortened lastridge ropes as a controlled treatment is required, considering this is a very simple, inexpensive modification. Certainly, there would be minimal benefit in using T90 codends made with 75- to 80-mm mesh in the CTS without shortened lastridge ropes, because eventually meshes will distort—unless thicker twine is used but, similar to the conventional 90-mm T0 mesh codends, this would concomitantly reduce lateral openings (Kennelly and Broadhurst, 2021).

For some species in the CTS, selectivity might also be improved via additional posterior and anterior trawl modifications, and especially those used to reduce catches of some discarded elasmobranchs (which accounted for one-third of discards here). Nevertheless, there is resistance to major gear changes in many fleets and so, initially, simple options are required (Kennelly and Broadhurst, 2021). Regulating a more appropriate mesh size and/or configuration in the codends of CTS trawlers would be a coherent starting point for ongoing efforts to improve selection.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Ethics statement

The animal study was approved by Regional NSW Fisheries Animal Care and Ethics Committee (Ref no: ARA-FISH-0419 (08/06) Testing selective fishing gears in NSW commercial fisheries). The study was conducted in accordance with the local legislation and institutional requirements.

Author contributions

MB: Conceptualization, Data curation, Formal Analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Validation, Visualization, Writing – original draft, Writing – review & editing. RM: Conceptualization, Data curation, Formal Analysis, Software, Visualization, Writing – review & editing.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fmars.2024.1341890/full#supplementary-material

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Supplementary material

Methods (relative size-selectivity analyses)
Generalized additive modelling (GAM) was used to fit relative size selectivity curves to key species among each of the three possible pairings of the codends. For example, for those tows involving the conventional 91-mm T0 and narrow 71-mm T90 codends, let n_l^{CT0} and n_l^{NT90} denote the number of length *l* fish caught. Then

$$p_l = \frac{n_l^{NT90}}{n_l^{CTO} + n_l^{NT90}}$$

is the proportion caught in the narrow 71-mm T90 codend. The expected value of p_l was modelled on the logit scale using cubic regression splines of dimension three, denoted *s(l)*. That is:

$$E[p_l] = \frac{\exp(s(l))}{1 + \exp(s(l))}$$

The error distribution of p_l was specified to be quasi-binomial to incorporate overdispersion from subsampling, whereby length frequencies were first scaled up by deployment subsampling fractions to estimate total frequencies. Confidence intervals were obtained using a 1000 iteration double bootstrap (Millar, 1993; Xu and Millar, 1993). The GAMs were fitted using the gam function within the mgcv package within R (Wood, 2017).

Results (mixed effects models)
The mixed effects modelling results (from R) for retained tiger flathead and latchet and discarded rounded-snouted gurnard are provided below. Note the results are given on the log (not the response) scale. The 95% confidence level ('emmeans' table) and Tukey method for comparing a family of three estimates for the *p*-value adjustment ('contrasts' table) were used.

Number of retained tiger flathead
> i=6; cat(VoI[i],"\n"); Gfit=FitList[[i]]; emmeans(Gfit, pairwise~Gear)
$emmeans

Gear	Emmean	SE	df	Asymp.LCL	Asymp.UCL
Wide 71-mm T90	-0.619	0.367	Inf	-1.339	0.101
Narrow 71-mm T90	-0.290	0.361	Inf	-0.999	0.418
91-mm T0	0.967	0.376	Inf	-1.703	-0.230

$contrasts

Contrast	Estimate	SE	df	Z ratio	*P*-value
Wide 71-mm T90 - narrow 71-mm T90	-0.329	0.280	Inf	-1.076	0.4678
Wide71-mm T90 - 91-mm T0	0.348	0.320	Inf	1.085	0.5235
Narrow 71-mm T90 - 91-mm T0	0.676	0.293	Inf	2.306	0.0550

Number of retained latchet
> i=18; cat(VoI[i],"\n"); Gfit=FitList[[i]]; emmeans(Gfit, pairwise~Gear)
$emmeans

Gear	Emmean	SE	df	Asymp.LCL	Asymp.UCL
Wide 71-mm T90	-4.50	0.977	Inf	-6.42	-2.590
Narrow 71-mm T90	-4.01	0.924	Inf	-5.82	-2.200
91-mm T0	-7.68	1.269	Inf	-10.16	-5.190

$contrasts

Contrast	Estimate	SE	df	Z ratio	*P*-value
Wide 71-mm T90 - narrow 71-mm T90	-0.492	0.534	Inf	-0.922	0.626
Wide71-mm T90 - 91-mm T0	3.173	1.086	Inf	2.923	0.0097
Narrow 71-mm T90 - 91-mm T0	3.665	1.087	Inf	3.373	0.0021

Number of discarded round-snouted gurnard

> i=29; cat(VoI[i],"\n"); Gfit=FitList[[i]]; emmeans(Gfit, pairwise~Gear)

$emmeans

Gear	Emmean	SE	df	Asymp.LCL	Asymp.UCL
Wide 71-mm T90	1.361	0.548	Inf	0.286	2.44
Narrow 71-mm T90	1.929	0.552	Inf	0.846	3.01
91-mm T0	0.951	0.576	Inf	-0.179	2.08

$contrasts

Contrast	Estimate	SE	df	Z ratio	*P*-value
Wide 71-mm T90 - narrow 71-mm T90	-0.568	0.499	Inf	-1.137	0.4910
Wide71-mm T90 - 91-mm T0	0.410	0.547	Inf	0.749	0.7340
Narrow 71-mm T90 - 91-mm T0	0.978	0.560	Inf	1.1747	0.1878

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Supplementary Table 1. Weights (wt, kg), numbers (no.), total-length ranges (TL in cm where available) and percentage discarded (by wt) of species caught during 39 deployments of the trawl attached to a conventional 91-mm T90 codend (12 deployments), and narrow (14) and wide (13) 71-mm T90 codends off south-eastern Australia between April and August 2023. Na, not available or applicable.

Variable	Wt	No.	TL	% discarded by wt
Total	28,185	Na	Na	
Teleosts				
Australian angelshark, *Squatina australis*	20.0	2	Na	0.0
Australian bonito, *Sarda australis*	3.8	5	Na	0.0
Australian burrfish, *Allomycterus pilatus*	184.8	394	Na	100.0
Barracouta, *Thyrsites atun*	5.7	26	Na	86.0
Barred grubfish, *Parapercis allporti*	84.2	632	7.0–27.0	100.0
Bigeye ocean perch, *Helicolenus barathri*	10.5	24	Na	0.0
Bigspine boarfish, *Pentaceros decacanthus*	0.8	8	Na	100.0
Black jewfish, *Protonibea diacanthus*	1.0	1	Na	100.0
Blackspot boarfish, *Zanclistius elevatus*	25.5	152	Na	100.0
Blacktip cucumberfish, *Paraulopus nigripinnis*	652.5	8306	9.0–27.5 Na	100.0
Blue mackerel, *Scomber australasicus*	17.8	71	Na	0.0
Blue morwong, *Nemadactylus valenciennesi*	7.6	7	Na	0.0
Blue warehou, *Seriolella brama*	0.2	1	Na	0.0
Bluespotted flathead, *Platycephalus caeruleopunctatus*	303.5	740	15.5–59.5	12.0
Bluestriped goatfish, *Upeneichthys lineatus*	29.1	144	Na	1.0
Bulldog stargazer, *Xenocephalus armatus*	80.1	204	Na	88.0
Butterfly gurnard, *Lepidotrigla vanessa*	4.4	25	Na	100.0
Cocky gurnard, *Lepidotrigla modesta*	2.0	38	Na	100.0
Common bellowsfish, *Macroramphosus scolopax*	4074.6	389558	Na	100.0
Common stargazer, *Kathetostoma leave*	21.0	18	Na	0.0
Common stinkfish, *Foetorepus calauropomus*	48.5	334	20.0–27.5	100.0
Eastern school whiting, *Sillago flindersi*	596.7	8677	12.5–26.5	0.1
Eastern smooth boxfish, *Anoplocapros inermis*	189.3	486	Na	100.0
Finespine pufferfish, *Tylerius spinosissimus*	0.8	1	Na	100.0
Flounder spp, *Paralichthys* spp.	23.2	181	Na	91.8
Rough flutemouth, *Fistularia petimba*	1.3	3	Na	100.0
Fourspine leatherjacket, *Eubalichthys quadrispinis*	3.7	4	Na	0.0
Frostfish, *Lepidopus caudatus*	2.0	2	Na	0.0
Gemfish, *Rexea solandri*	56.9	283	22.5–29.0	66.6
Giant boarfish, *Paristiopterus labiosus*	4.7	11	Na	42.6
Grey morwong, *Nemadactylus douglasii*	103.8	343	Na	26.9
Jack mackerel, *Trachurus declivis*	0.3	3	Na	0.0
Jackass morwong, *Nemadactylus macropterus*	50.7	181	Na	7.3
John dory, *Zeus faber*	111.1	202	Na	2.1
Latchet, *Pterygotrigla polyommata*	234.3	326	27.0–47.0	2.3
Little whiptail, *Coelorinchus gormani*	58.5	730	19.5–26.5	100.0
Longfin bigeye, *Cookeolus japonicus*	5.4	31	Na	40.7
Mackerel tuna, *Euthynnus affinis*	1.1	1	Na	0.0
Manyband sole, *Zebrias scalaris*	0.4	4	Na	100.0
Mirror dory, *Zenopsis nebulosa*	7.1	12	Na	0.0
Miscellaneous fish	24.6	699	Na	100.0
Mosaic leatherjacket, *Eubalichthys mosaicus*	1.0	1	Na	0.0
Ocean jacket, *Nelusetta ayraud*	25.0	72	Na	47.6
Painted latchet, *Pterygotrigla andertoni*	180.0	1784	13.0–21.0	100.0
Pike, *Dinolestes lewini*	6.0	10	Na	100.0
Pink ling, *Genypterus blacodes*	20.5	19	Na	0.0
Pufferfish, Triodontidae	302.1	1268	Na	100.0
Red cod, *Pseudophycis palmata*	3.6	5	Na	8.3
Red gurnard, *Chelidonichthys kumu*	415.7	862	Na	12.5
Redbait, *Emmelichthys nitidus*	2.5	25	Na	100.0
Redfish, *Centroberyx affinis*	1049.4	6276	12.0–30.5	26.5
Reef ocean perch, *Helicolenus percoides*	141.4	738	13.5–27.0	4.5
Round-snouted gurnard, *Lepidotrigla mulhalli*	3240.2	60018	9.0–29.5	100.0
Sergeant baker, *Latropiscis purpurissatus*	18.9	24	Na	95.2
Shortspine porcupinefish, *Cyclichthys orbicularis*	4.2	6	Na	100.0
Silver dory, *Cyttus australis*	6.8	13	Na	0.0
Silver trevally, *Pseudocaranx georgianus*	1704.7	6915	20.0–39.0	0.0
Silver warehou, *Seriolella punctata*	137.0	400	28.0–37.5	0.7
Smooth golden toadfish, *Lagocephalus inermis*	1.7	6	Na	100.0
Snapper, *Chrysophrys auratus*	15.2	22	Na	9.9
Splendid perch, *Callanthias australis*	5.0	25	Na	0.0
Spotted bigeye, *Priacanthus macracanthus*	39.2	224	18.5–22.0	36.5
Tailor, *Pomatomus saltatrix*	209.9	725	25.0–36.5	0.0
Tiger flathead, *Platycephalus richardsoni*	2221.8	6347	18.0–60.5	22.3
Triggerfish and leatherjacket, Monacanthidae	14.0	109	Na	89.3
Velvet leatherjacket, *Meuschenia scaber*	215.8	1026	Na	100.0
Yellowfin tuna, *Thunnus albacares*	1.0	1	Na	0.0
Yellowtail kingfish, *Seriola lalandi*	4.0	4	Na	0.0
Yellowtail scad, *Trachurus novaezelandiae*	28.2	215	12.0–35.5	100.0

Elasmobranchs				
Blackfin ghostshark, *Hydrolagus lemures*	12.0	6	Na	0
Common blacktip shark, *Carcharhinus limbatus*	7.0	1	Na	0
Common sawshark, *Pristiophorus cirratus*	724.6	664	Na	33.9
Common stingaree, *Trygonoptera testacea*	38.4	49	Na	100
Eastern angel shark, *Squatina albipunctata*	1074.3	334	Na	0.6
Eastern shovelnose ray, *Aptychotrema rostrata*	501.3	285	Na	6.8
Eastern shovelnose stingaree, *Trygonoptera imitata*	0.8	4	Na	100
Greenback stingaree, *Urolophus viridis*	0.6	2	Na	100
Gummy shark, *Mustelus antarcticus*	105.2	31	Na	1.1
Kapala stingaree, *Urolophus kapalensis*	32.0	108	Na	100
Melbourne skate, *Spiniraja whitleyi*	15.0	1	Na	0
Peacock skate, *Pavoraja nitida*	8.6	35	Na	100
Port Jackson shark, *Heterodontus portusjacksoni*	402.5	207	Na	100
Rusty carpetshark, *Parascyllium ferrugineum*	100.7	115	Na	100
Sandyback stingaree, *Urolophus bucculentus*	194.0	259	Na	92.5
Sawtail catshark, *Figaro boardmani*	107.4	347	Na	100
Short-tail torpedo ray, *Tetronarce nobiliana*	78.0	4	Na	100
Skate, Arhynchobatidae	20.0	67	Na	100
Smooth hammerhead, *Sphyrna zygaena*	1.2	1	Na	100
Smooth stingray, *Bathytoshia brevicaudata*	702.0	27	Na	100
Southern eagle ray, *Myliobatis tenuicaudatus*	593.5	506	Na	7.8
Southern fiddler ray, *Trygonorrhina dumerilii*	3127.0	1130	Na	100
Southern sawshark, *Pristiophorus nudipinnis*	15.9	24	Na	87.4
Sparsely-spotted stingaree, *Urolophus paucimaculatus*	10.4	41	Na	100
Spikey dogfish, *Squalus megalops*	394.6	789	Na	100
Spotted wobbegong, *Orectolobus maculatus*	0.4	4	Na	100
Stingaree spp., *Urolophus* spp.	1050.1	4355	Na	100
Stingray spp., *Bathytoshia* spp.	2.5	1	Na	100
Sydney skate, *Dentiraja australis*	121.5	225	Na	100
Tasmanian numbfish, *Narcinops tasmaniensis*	21.8	172	Na	100
White shark, *Carcharodon carcharias*	30.0	1	Na	100
Whitespotted skate, *Dentiraja cerva*	222.5	353	Na	100
Yellowback stingaree, *Urolophus sufflavus*	46.8	130	Na	100
Cephalopods				
Cuttlefish, *Sepia* spp.	48.7	170	Na	5.6
Gould squid, *Nototodarus gouldi*	112.0	233	Na	5.0
Octopus, Octopodidae	51.9	104	Na	0.0
Southern calamari, *Sepioteuthis australis*	11.1	18	Na	0.0
Gastropods				
Australian tulip shell, *Australaria australasia*	0.3	1	Na	0.0
Dog whelk, *Nassarius burchardi*	12.0	50	Na	0.0
False bailer shell, *Livonia mammilla*	0.6	1	Na	0.0
Whelk, Babyloniidae	2.0	7	Na	0.0

Appendix 12. Broadhurst, M.K. and Millar, R.B. 2025. Effects of headline height on catches in southeastern Australian fish trawls. Fish. Res. 281, 107219. doi:10.1016/j.fishres.2024.107219

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Full length article

Effects of headline height on catches in southeastern Australian fish trawls

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ABSTRACT

Benthic fish trawls are used off southeastern Australia to target multiple species that have similar sizes and morphologies to non-target species. These characteristics mean there are limited options for improving selectivity via changes to meshes and/or bycatch reduction devices in the codend. Consequently, simple modifications to the anterior trawl body that potentially exploit behavioural differences to separate species before entry have been prioritised for testing. Optimising trawl headline height is recognized as important for refining selectivity, but causal effects can be difficult to isolate owing to variability among confounding operational or technical factors (such as variable spread ratios, ground gears, and/or towing speeds). Here we attempted to isolate the effects of headline height by alternately fishing a conventional trawl (mean headline height ± SE of 3.76 ± 0.07 m) with a design that was identical in key aspects, but had a ~22 % reduction in fishing circumference at the mouth and therefore a similar lower average headline height (2.75 ± 0.07 m) across homogenous operational variables. There were no significant differences in the numbers and weights of retained and discarded species between the two trawls, although mean catches of the primary target, tiger flathead, *Platycephaus richardsoni* were ~25 % lower in the low trawl, implying this species orientates across the range of conventionally fished heights. Regardless of the trawl, there was a significant, negative main effect of headline height on the weights of total discards and two abundant batoids (smooth stingray, *Bathytoshia brevicaudata* and greenback stingaree, *Urolophus viridis*) attributed to lower ground-gear contact pressure and/or an increased footrope height of both trawls, facilitating the escape of some individuals under the trawl. The only other species affected by headline height was velvet leatherjacket *Meuschenia scaber*, with catches increasing as headline increased; possibly owing to changes in netting panel angles at the trawl mouth that precluded escape. It should be possible to marginally reduce the circumference at the mouth of regional trawls and so reduce headline height and at least some drag while maintaining target catches. More broadly, it appears that regardless of the trawl-body circumference, headline height can indirectly affect species selectivity via concomitant effects on other gear components.

1. Introduction

In Australia, there exist ~118 licences permitting benthic otter trawling to target fish, with participating vessels distributed off most states and territorial waters, although >60 % of all effort is focused along the southeastern coast. More specifically, 43 licenses are state managed in New South Wales (NSW; mostly inshore and fishing <100 m), while 30 licences operate within the federally regulated 'Commonwealth trawl sector' (CTS) extending offshore (to ~700 m) from central NSW around Victoria and Tasmania to Cape Jervis, South Australia (Novaglio et al., 2018).

Regardless of the jurisdiction, all southeastern Australian benthic fish trawlers typically tow 30–45 m headline-length trawls with a minimum stretched mesh opening (SMO) of 90 mm in the codend to target ~20 species; among which tiger flathead, *Platycephalus richardsoni* (caught at <200 m depths and at minimum legal sizes—MLS of 33 and 28 cm total length—TL in NSW and the CTS, respectively) is often dominant (~25 % of total catches) (Graham et al., 2009). All trawlers also retain >100 other species listed as commercially important 'by-product' for totals of ~1200 and 12,000 t p.a. in NSW and the CTS,

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respectively. As for all benthic-trawl fisheries around the planet (Kennelly and Broadhurst, 2021), those off southeastern Australia generally have high levels of bycatch which can comprise >280 species and 40–60 % by weight of the total catches (Graham et al., 2009; Knuckey and Ashby, 2009; Broadhurst et al., 2023a; b; Broadhurst and Millar, 2024). High associated unaccounted fishing mortalities have raised some sustainability concerns.

There are similarities in sizes and morphologies among many target, by-product and bycatch species in southeastern Australian fish-trawl catches which mostly preclude investigating modifications to trawls that exploit mechanical processes to control selection (e.g. larger mesh sizes) (Broadhurst and Millar, 2024). For any reduction in bycatch, there is likely to be at least some concomitant loss of target or by-product catches (Knuckey and Ashby, 2009). An alternative approach is to consider modifications that separate species based on behaviour; ideally at the anterior trawl where any mortalities or sublethal impacts to escaping fish are likely to be lower than for those at the codend (Broadhurst et al., 2006; McHugh et al., 2017).

One of the simplest methods for regulating the types of species, and potentially their sizes, entering a fish trawl, is by varying the headline height (Rose and Nunnallee, 1998). However, changes to headline height typically are achieved in conjunction with, or because of, various other trawl-geometry changes which can partially confound isolating effects (Fiorentini et al., 1999; Hannah et al., 2005; Cartes et al., 2009; Krag et al., 2015). Nevertheless, within any trawl configuration, optimizing headline height is essential for maximizing efficiency and requires some interpolation of species-specific behaviour (Engås et al., 1999). Because southeastern Australian fish trawlers are single rigged (precluding simultaneous comparisons), operators have limited assessment options beyond approximating required headline heights based on associated catches. Many fishers assume their trawls reach ~3–5 m in height, although few have electronic trawl-monitoring equipment. Recent trials testing generic inshore trawls with trawling-monitoring systems have recorded average headline heights within this range (3.8–4.4 m; Broadhurst et al., 2023a; b). Such configurations are clearly sufficient in terms of targeted catches, but the benefits of empirically determining an optimal headline height extend beyond species selectivity. Specifically, even minor reductions in headline height will concomitantly reduce trawl drag and fuel use owing to the lower angled netting creating less resistance and/or fewer meshes in circumference which reduces twine area (O'Neill and Breddermann, 2024).

While there are few empirical studies assessing the vertical distributions (Broadhurst et al., 2023a) and/or behaviours (Piasente et al., 2004; Yanase et al., 2009) of fish entering Australian fish trawls, there are at least some subtle species-specific patterns that might inform optimal headline heights. For example, using video cameras during the day Piasente et al. (2004) and Yanase et al. (2009) observed platycephalids, including tiger flathead, mostly remained low during entry into trawls. These observations were supported by Broadhurst et al. (2023a), who diurnally fished a horizontal-separator panel in the aft 50 % body of a conventional trawl (with a headline height of ~4 m) and showed nearly 80 % of all tiger flathead (including most larger fish) entered the lower section. Many other species, including elasmobranchs (which can comprise >30 % of discards), also remained low, but some, such as the smooth stingray, *Bathytoshia brevicaudata*, orientated towards the upper trawl (Broadhurst et al., 2023a). Such behaviour might be exploited via subtle changes to headline height to reduce bycatches.

Considering the above, here we sought to investigate the effects of reducing the headline height of a generic CTS trawl targeting tiger flathead inshore off southeastern Australia on retained and discarded catches. This hypothesis was investigated by alternately comparing catches from a conventional trawl designed to fish at a headline height approaching 4 m to those from an almost identical design reconfigured with ~22 % fewer meshes in the fishing circle to fish at a headline height of <3 m.

2. Methods

The work was completed off Ulladulla (35.36°S; 150.47°E) and Bermagui, NSW (36.43°S; 150.08°E) during April and May 2024 using a chartered, single-rigged 20-m fish trawler (FV *Imlay*) fishing across commercial tiger flathead grounds (60–200 m). The vessel was equipped with dual net drums that held two trawls (described below); each of which was attached to identical 22-m bridles (made from 26-mm diameter—Ø combination wire) (STable 1). The trawls could be alternatively secured to the same 274-m sweeps and steel-otter boards (600 kg each) (STable 1). A Notus trawl monitoring system was used to record otter-board spread and headline height (m), while a Lowrance global position system (GPS) and echosounder were used to record the distance travelled (km), average speed over the ground (SOG; ms^{-1}) and depth (m), respectively.

2.1. Treatment trawls

Two new trawls were constructed from identical polyethylene mesh (PE) for use in the experiment (STable 1, Fig. 1). Both trawls had identical headlines (40 m of 16-mm Ø Dynema®), footropes (34 m of 20-mm Ø PE wrapped wire cable), ground gears (34 m of 60- and 130-mm Ø rubber discs and weighing 250 kg) suspended from 195-mm long, 13-mm Ø chain drops, ground-gear extensions (same configurations as ground gears), overall lengths (63 m) and mesh sizes (STable 1, Fig. 1).

All prefabricated panels of mesh were measured for SMO and twine Ø (between 30 and 80 replicates) using a legislated gauge and vernier callipers, respectively (STable 1). The mean (±SE) SMOs and twine Øs included 141.4 (0.13) and 4.4 (0.04) mm for frame-line reinforcements attached to 147.7 (0.20) and 2.5 (0.03) mm in the top wings and anterior trawl, and 114.8 (0.08) and 2.3 (0.02) mm in the lower wings and anterior trawl, transitioning to 97.2 (0.11) and 2.2 (0.02) mm in the posterior body, 103.5 (0.16) and 3.5 (0.01) mm in the extension and 92.8 (0.16) and 7.2 (0.02) mm in the codend (STable 1, Fig. 1a). Each trawl had 33.5 meshes (~5 m stretched) of lead-ahead and V-shaped wing ends (Fig. 1a and b).

The only differences between trawls were the numbers of meshes in the depths of the wings, around the mouth and then tapering back towards the extension, and the number of floats (STable 1, Fig. 1a). Specifically, the first trawl (termed 'conventional trawl') represented the generic upper limit of mesh volume at the mouth for regional inshore trawlers, with an estimated fishing circumference (number of meshes × SMO × 0.35) of ~17.7 m and was designed to fish at a headline height of ~3.5–4.0 m, with 50 × 200-mm Ø spherical floats evenly distributed along the headline. The second treatment trawl (termed the 'low trawl') had ~22 % fewer meshes at the mouth for an estimated fishing circumference of 13.8 m and, assuming dilation, at least a 22 % reduction in headline height (i.e. to maintain similar mesh openings; STable 1, Fig. 1a). The low trawl was rigged with 42 of the same 200-mm Ø spherical floats (STable 1, Fig. 1).

2.2. Experimental design and data collection

On each of 12 fishing days, the two trawls were alternately deployed twice between 02:30 and 16:30 for up to 2.9 h. The technical data collected during each deployment include the: trawled location; distance (km) and duration (h; warp winch brakes on and off); otter-board spread (m); headline height (m); speed over the ground (SOG) (ms^{-1}); and depth (m) of the trawl. The latter four variables were logged every ~5–15 min to provide averages for each deployment. We attempted to standardize otter-board spread within days (and for any depth) by slightly adjusting the deployed warp lengths between trawls, while maintaining the same SOG. The trawl distance and average otter-board spread were used to calculate the ha trawled.

At the end of the deployment, the codend was emptied into an enclosed on-deck pen with a known volume and the total catch weight

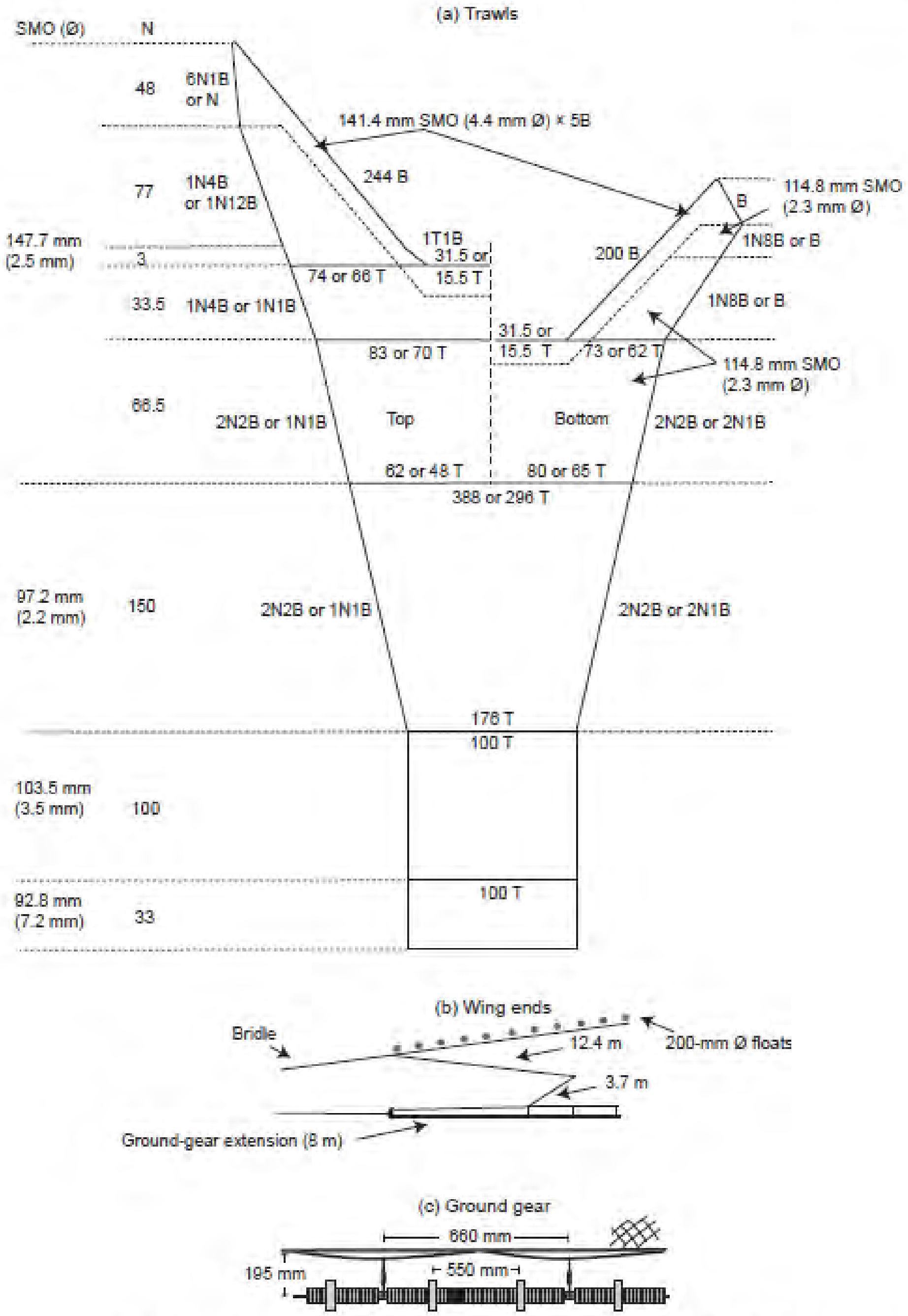

Fig. 1. Plans of the (a) conventional and low trawls with their identical (b) wing ends and (c) ground gears that were fished during the experiment. Ø, diameter; N, normal direction; T, transverse direction; mesh size is stretched mesh opening (SMO); twine Ø in parentheses.

was estimated. Retained individuals of target and by-product species larger than minimum commercial (or legal for tiger flathead) TLs were separated into 55-l boxes, and weighed and counted, before subsamples of up to 100 individuals of key teleosts (e.g. the abundant commercial species, especially tiger flathead) were measured to the nearest 0.5 cm TL. The total bycatch weight was then estimated by subtracting the retained catch from the total, and random subsamples (up to two 55-l boxes) were collected with all species counted and weighed and some (typically juveniles of commercially important species) were measured as above.

2.3. Data analyses

The technical and catch data were analysed using various linear mixed models (LMM); all of which included the random effect of 'days'. For otter-board spread, the fixed effects in the LMM included the categorical 'trawl' and continuous 'SOG' and 'depth'. The analyses of headline height as a response included these parameters and also 'otter-board spread' as a fixed continuous effect. Other technical response data, including deployment duration, SOG, depth and swept area, were analysed in LMMs limited to the fixed effect of trawl only (i.e. to test the null hypothesis of no differences between the key treatments of interest). Catch data (numbers and weights) were standardized to ha^{-1} trawled (between the otter boards) before being log-transformed to act multiplicatively and analysed in LMMs with the main effects of trawl and headline height and their interaction. Model diagnostics included checking QQ tests and plots of residuals, before the significance of fixed effects was determined using Wald-*F* tests. Mean catches of abundant retained and discarded species/groups of interest in each trawl were plotted.

For those abundant species measured in sufficient quantities, cubic regression splines were used to fit catch-share curves for the proportion of the total scaled-up catch (over the conventional and low trawls) of each TL that was caught in the conventional trawl (Broadhurst et al., 2018). This analysis was implemented using the SELECT R package (Millar, 1992; 2021) which includes bootstrap functionality (Millar, 1993) to incorporate between-haul variability (Millar et al., 2004). The SELECT package also includes a function for permutation tests, which were used to test for no TL effects due to trawl (i.e. the catch share was the same for all TLs; Broadhurst et al., 2022). The bootstraps and simulations both used 1000 iterations, and all analyses were done in R (R Core Team, 2021).

3. Results

3.1. Technical data

In total, 24 and 23 replicates were completed for the conventional and low trawls, respectively. All technical data were collected for all tows, except otter-board spread for two and three deployments of the conventional and low trawls, respectively, and headline height for a single replicate of the conventional trawl. These data were missing owing to low batteries in the otter-board sensors and incorrect insertion of the headline sensor. Analyses of technical variables were done on the remaining data, although the mean otter-board spreads were used to estimate swept area and to standardize catches (below).

There were no significant differences between the conventional and low trawls for their deployment durations, SOGs, depths fished, otter-board spreads or areas trawled (LMM, $p > 0.05$; Table 1). Otter-board spread was negatively correlated with depth (LMM, $p < 0.05$; Table 1). Headline height was significantly different between trawls ($p <$ 0001; Table 1), ranging from 3.3 to 4.4 m for the conventional and from 2.3 to 3.5 m for the low, but was not significantly affected by any of the other measured covariates (LMM, $p > 0.05$; Table 1).

3.2. Biological data

The total catch across the 47 deployments was 28.2 t, of which 11.3 t was retained (i.e. 60 % discarded; STable 2). Among the retained catches, tiger flathead was dominant (37.8 % by weight and nearly all were legal sized) with five other species caught in sufficient quantities (totalling ~25 % of all retained) to permit analysis (Table 2). Key discards included roundsnout gurnard, *Lepidotrigla mulhalli* (22.7 % of discards), southern fiddler ray, *Trygonorrhina dumerilii* (17.2 %), greenback stingaree, *Urolophus viridis* (9.8 %) and smooth stingray (8.7 %) which, along with nine others, comprized 77.4 % of all discards (STable 2 and Table 2).

Linear mixed models revealed no significant differences in the numbers and weights of any catches between trawls, although the *p*-value was 0.06 for the weight of retained tiger flathead, with 28 % fewer retained in the low trawl, and a similar non-significant trend (25 % fewer) for the numbers (Fig. 2, Table 2). The differences in mean catches of other abundant species were variable but ranged from up to 47 % fewer discarded velvet leather jacket to twice-as-many discarded southern fiddler ray in the low trawl ($p > 0.05$; Table 2, Fig. 2g and j). The only significant effects in the LMMs were for headline height (regardless of the trawl) on the weights of total discarded catch, smooth stingray and velvet leatherjacket and the numbers and weights of greenback stingaree ($p < 0.05$; Table 2, Fig. 2). For all variables, except the weight of velvet leatherjacket, the regression co-efficient was negative (Table 2).

Sufficient size data were collected for tiger flathead, roundsnout gurnard, red gurnard, velvet leatherjacket and eastern school whiting to produce informative plots of length distributions (Fig. 3). Plots of relative size-frequencies indicated the conventional trawl retained proportionally more smaller tiger flathead, but fewer smaller individuals of all other species than the low trawl except for roundsnout gurnard which were similar across all sizes (Fig. 3). Nevertheless, all catch-share curves were characterized by considerable between-haul variability, with the five permutation tests all having *p*-values exceeding 0.1, indicating no effects of TL on catches (Fig. 3).

4. Discussion

This study contributes towards the few attempts at quantifying the effects of headline height in fish trawls, while reducing the impacts of

Table 1
Summaries of Wald *F*-values from linear mixed models assessing the importance of relevant fixed effects on technical responses, and the overall mean (SE) values for each trawl (conventional and low). 'Days' were included as a random blocking factor.

Variable	Trawls	Otter-board spread	SOG	Depth	Conventional	Low
Otter-board spread (m)	1.5	–	4.9	6.2*	133.41 (1.63)	135.78 (1.27)
Headline height (m)	89.9***	0.0	0.7	0.0	3.76 (0.07)	2.75 (0.07)
Deployment duration (h)	0.5	–	–	–	2.20 (0.08)	2.16 (0.04)
Depth (m)	0.3	–	–	–	103.20 (4.83)	101.60 (5.35)
Speed over the ground (SOG; ms^{-1})	2.2	–	–	–	1.59 (0.01)	1.57 (0.01)
Area trawled (ha)	0.2	–	–	–	168.39 (6.64)	165.30 (3.77)

* $p < 0.05$;
*** $p < 0.001$; –, not applicable

Table 2
Summaries of Wald *F*-values from linear mixed models assessing the importance of 'trawls' (conventional and low), 'headline height' and their interaction on biological data, and the mean (SE) catches trawled ha^{-1} for each trawl. 'Days' were included as a random blocking factor.

	Trawls (T)	Headline height (H)	T × H	Conventional	Low
Retained catches					
Wt of total	0.1	1.5	0.2	1.55 (0.18)	1.42 (0.14)
No. of tiger flathead	2.4	0.0	0.3	1.61 (0.18)	1.24 (0.16)
Wt of tiger flathead	3.9	0.1	0.0	0.68 (0.07)	0.49 (0.06)
No. of common saw shark	0.7	1.8	0.0	0.07 (0.02)	0.07 (0.02)
Wt of common saw shark	0.3	1.4	0.0	0.16 (0.07)	0.16 (0.05)
No. of red gurnard	2.3	0.1	3.8	0.27 (0.05)	0.30 (0.11)
Wt of red gurnard	3.0	0.1	3.0	0.12 (0.02)	0.12 (0.04)
No. of grey morwong	2.2	2.4	1.2	0.15 (0.06)	0.05 (0.02)
Wt of grey morwong	2.1	2.3	1.0	0.07 (0.02)	0.03 (0.01)
No. of eastern school whiting	0.3	1.4	0.0	0.79 (0.61)	0.58 (0.34)
Wt of eastern school whiting	0.1	2.2	0.1	0.06 (0.05)	0.04 (0.02)
No. of Gould's squid	2.7	2.7	0.6	0.03 (0.01)	0.02 (0.01)
Wt of Gould's squid	3.3	1.9	0.9	0.02 (0.00)	0.01(0.00)
Discarded catches					
Wt of total	0.1	6.4*(–)	1.4	2.26 (0.35)	2.23 (0.37)
No. of roundsnout gurnard	0.3	0.8	0.0	10.88 (4.21)	8.28 (3.07)
Wt. of roundsnout gurnard	1.1	1.2	0.1	0.63 (0.23)	0.41 (0.15)
No. of southern fiddler ray	2.4	0.1	1.4	0.05 (0.02)	0.14 (0.04)
Wt of southern fiddler ray	1.8	0.2	1.9	0.25 (0.11)	0.44 (0.14)
No. of greenback stingaree	0.0	6.2*(–)	1.3	0.66 (0.26)	0.35 (0.11)
Wt of greenback stingaree	0.0	5.8*(–)	1.2	0.24 (0.08)	0.16 (0.05)
No. of smooth stingray	0.3	1.4	0.0	0.01 (0.0)	0.01 (0.0)
Wt of smooth stingray	0.1	7.8**(–)	0.0	0.20 (0.06)	0.16 (0.05)
No. of Australian burrfish	0.0	0.0	2.4	0.26 (0.05)	0.22 (0.05)
Wt of Australian burrfish	0.1	0.0	3.2	0.13 (0.03)	0.09 (0.01)
No. of velvet leatherjacket	1.6	4.0	0.0	1.33 (0.50)	0.72 (0.24)
Wt of velvet leatherjacket	1.2	5.3*(+)	0.2	0.17 (0.06)	0.09 (0.02)
No. of sparsely spotted stingaree	1.9	0.0	0.0	0.26 (0.15)	0.26 (0.07)

Table 2 (*continued*)

	Trawls (T)	Headline height (H)	T × H	Conventional	Low
Wt of sparsely spotted stingaree	1.9	0.3	0.0	0.04 (0.01)	0.09 (0.03)
No. of whitespotted skate	0.1	1.5	0.0	0.13 (0.03)	0.12 (0.02)
Wt of whitespotted skate	0.3	0.9	0.2	0.07 (0.02)	0.06 (0.01)
No. of yellowback stingaree	0.1	0.2	0.1	0.12 (0.03)	0.15 (0.04)
Wt of yellowback stingaree	0.3	0.2	0.1	0.05 (0.01)	0.07 (0.02)
No. of cocky gurnard	0.0	0.0	2.4	0.36 (0.12)	0.56 (0.26)
Wt of cocky gurnard	0.0	0.0	3.3	0.04 (0.02)	0.03 (0.01)
No. of grey morwong	0.8	2.3	0.8	0.32 (0.15)	0.19 (0.06)
Wt of grey morwong	1.0	2.3	0.9	0.06 (0.03)	0.04 (0.01)
No. of blacktip cucumberfish	0.4	2.8	0.1	0.81 (0.29)	0.53 (0.18)
Wt of blacktip cucumberfish	0.7	3.3	0.1	0.05 (0.02)	0.03 (0.01)
No. of common bellowsfish	0.0	1.8	0.8	0.79 (0.37)	1.12 (0.72)
Wt of common bellowsfish	0.0	1.1	0.4	0.01 (0.00)	0.01 (0.00)
No. of tiger flathead	0.2	0.0	0.1	0.22 (0.14)	0.10 (0.03)
Wt of tiger flathead	0.1	0.2	0.4	0.03 (0.02)	0.01 (0.00)

No., number; Wt, weight; the directions of significant coefficients are in parentheses; $^{*}p < 0.05$; $^{**}p < 0.01$

other known, confounding technical variables (Rose and Nunnallee, 1998; Fiorentini et al., 1999; Hannah et al., 2005; Cartes et al., 2009; Krag et al., 2015). In doing so, the work implies both direct and indirect effects of headline height on catches. More specifically, the direct effects manifested as a trend (albeit non-significant) for fewer tiger flathead in the low trawl, while regardless of trawl design, the indirect effects included significantly lower catches of two batoids and greater catches of velvet leatherjacket with increasing headline height. These observations can be discussed with respect to the mostly consistent trawl geometry (excluding headline height), but variable species-specific responses, and ultimately used to postulate trawl modifications for future testing or use off southeastern Australia.

To isolate the effects of headline height which was the key difference separating the primary treatment of interest (trawls), we sought to remove confounding effects of variable geometries. Specifically, we maintained standardized parameters among technical variables affecting size and species catchability, including mesh size and twine diameter (Broadhurst et al., 2000), sweep (Engås and Godø, 1989) and bridle lengths (Somerton and Munro, 2001), frame-line and ground-gear lengths (Cartes et al., 2009), lead-ahead (Broadhurst and Sterling, 2020), ground-gear weight and design (Brinkhof et al., 2017), spread ratio (i.e. horizontal trawl opening; Rose and Nunnallee, 1998) and otter boards (Broadhurst et al., 2012). While wing-end spread was not measured, the standardized parameters above combined with minimal assumed sweep curvature (i.e. straight-line geometry), means any variation in otter-board spread would have linearly affected wing-end

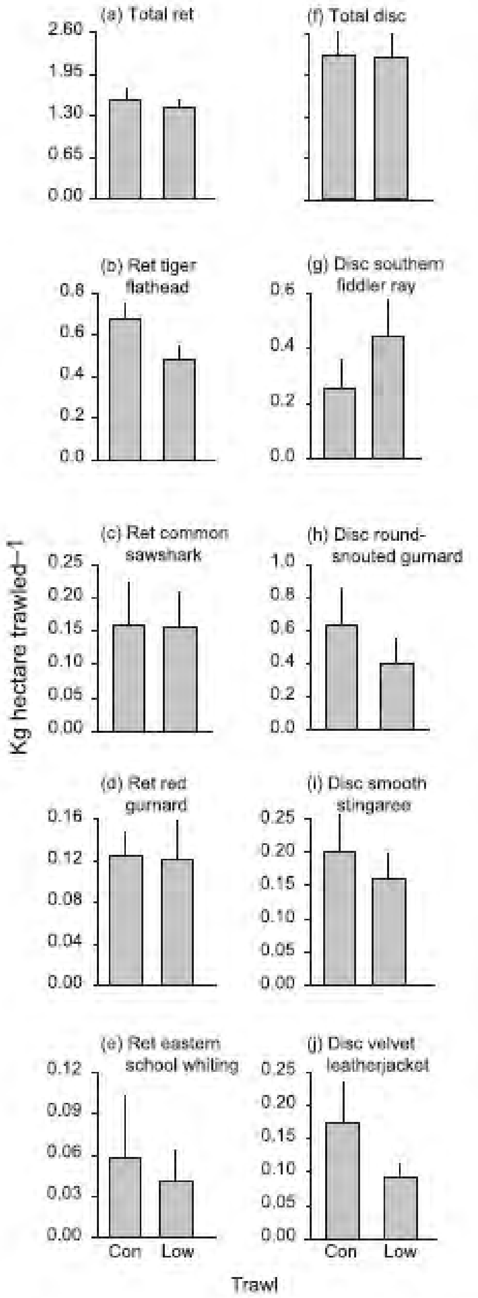

Fig. 2. Differences in mean (+SE) weights ha^{-1} trawled between the conventional and low trawls for retained (a) total catch, (b) tiger flathead, *Platycephalus richardsoni*, (c) common saw shark, *Pristiophorus cirratus*, (d) red gurnard, *Chelidonichthys kumu*, and (e) eastern school whiting, *Sillago flindersi* and discarded (f) total catch, (g) southern fiddler ray, *Trygonorrhina dumerilii*, (h) roundsnout gurnard, *Lepidotrigla mulhalli*, (i) smooth stingray, *Bathytoshia brevicaudata*, and (j) velvet leatherjacket, *Meuschenia scaber*. Ret, retained; Disc, discarded; Con, conventional.

spread, and so the latter should have also remained consistent between trawls. Consequently, it might be expected that any fish entering the path of the otter boards, sweeps and bridles were exposed to similar visual and tactile stimuli as they were herded towards the mouths of the trawls.

A key inter-trawl difference was the necessarily more acute bridle angle in the low trawl, commensurate with the lower average headline height. However, the reduction in headline height of the low trawl (−22 % of the conventional trawl) was very close to the reduction in mesh circumference at the trawl mouth—implying dilation in shape. Such geometric consistency should have resulted in similar lateral-mesh openings throughout the wings and anterior body. To achieve an identical overall length, the low trawl did have a shallower side taper, but this would be less important than length in terms of tiring and heading fish to the codend (Wardle, 1989).

Considering the similar geometries, any differences in catches would be expected to inform species-specific vulnerabilities in terms of vertical orientation. And so clearly, the lack of any significant effects of trawls implies most species maintained relatively low orientations, which supports the possibility for at least partially reducing headline height in the fishery (and with implied concomitant reductions in drag). Nevertheless, and while not significant, the mean reduction in catches of retained tiger flathead (23 and 28 % in numbers and weights) by the low trawl closely reflected the reduction in headline height, suggesting at least some individuals orientated upwards at the trawl mouth and/or wings and escaped over the headline. This percentage difference is also similar to that previously observed by Broadhurst et al., (2023a) for tiger flathead orientating in the upper section of a separated trawl body.

While there were no significant effects of trawls on any catches, regardless of the design, there were significant effects of headline height on three species. One possible explanation for the apparent negative effect of headline height (regardless of trawl type) on the catches of batoids (and total discards) involves changes to ground gear and contact pressure (Rose and Nunnallee, 1998). No monitoring equipment was available, but because the drops (195 mm) were flexible, the footrope may have changed height relative to the ground gear and increased at higher headlines while decreasing at lower headlines. Also, the pressure of the ground gear on the bottom was likely reduced with increased headline heights (Rose and Nunnallee, 1998). Possibly some greenback stingarees and smooth stingrays (both quite large species) were able to either escape through increased gaps between the footrope and ground gear and/or force their way under the ground gears of both trawls as headline heights increased. The contribution of these two species to total discard weight evoked the same significant negative effect of headline height on that variable.

The significant positive effect of headline height on catches of velvet leatherjacket was unlikely to be affected by any ground-gear changes, with the result further supported by relatively greater (by 48 %)—albeit non-significant—mean catches in the conventional trawl. Catches of velvet leatherjacket were highly variable between deployments, although possibly (and like for tiger flathead), some individuals were able to rise at the wings or mouth and escape over the lower ranges of headline heights in both trawls.

While more data are required to test hypothesis concerning the effects of headline height on the assessed and other locally caught species, the lack of significant differences between trawls here imply it should be possible to marginally reduce the circumference at the mouth of regional trawls and so reduce headline height and at least some drag. More broadly, it appears that regardless of the trawl body circumference, headline height can indirectly affect species selectivity via changes to other gear components. If these components include ground gear contact pressure and/or footrope height, then any impacts warrant closer assessment, both in terms of bycatch reduction and for trawl surveys (McHugh et al., 2917). Such research would benefit from using cameras and trawl sensors to directly monitor fish behaviour and ground-gear contact, respectively and with robust spatio-temporal replication. This

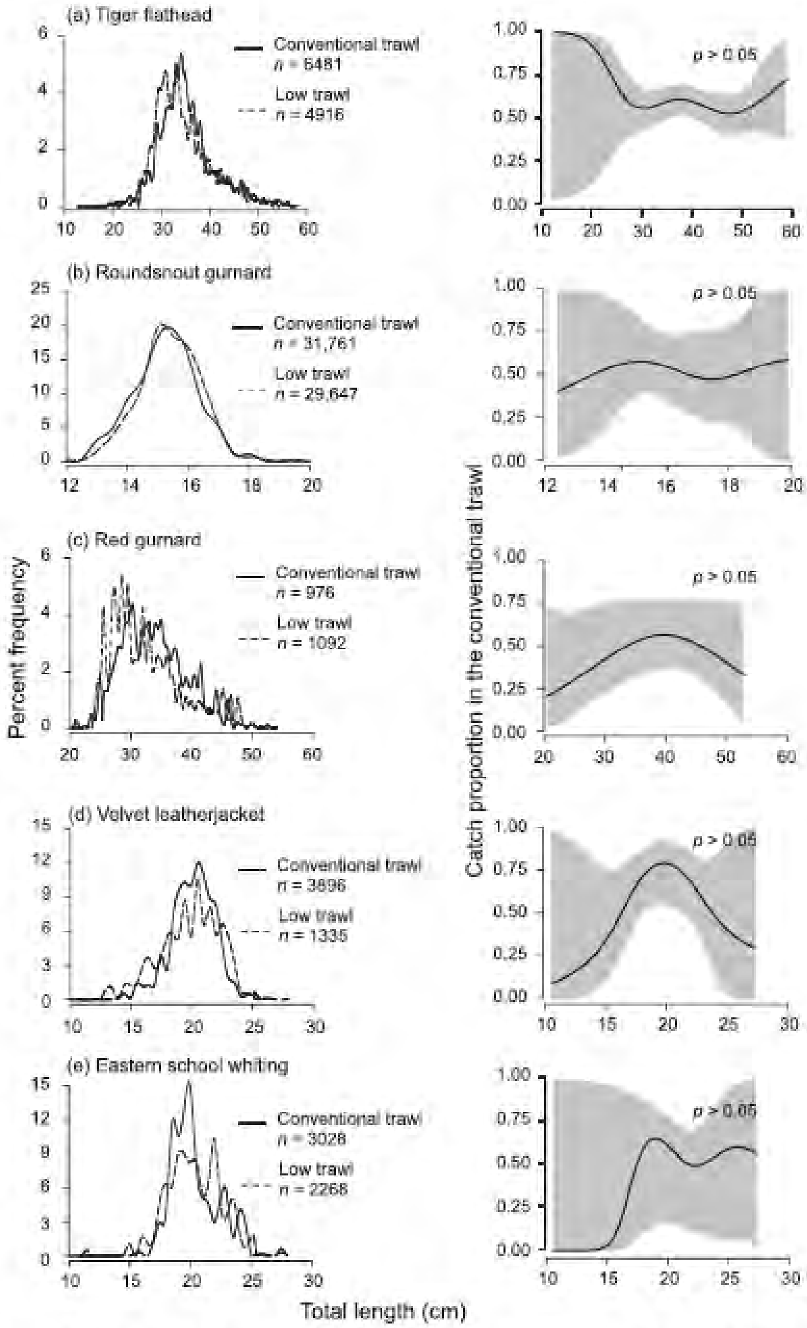

Fig. 3. Relative size-frequency distributions between trawls and the proportions of the scaled-up catches for each total length (TL; over both trawls) that were retained in the conventional trawl for (a) tiger flathead, *Platycephalus richardsoni*, (b) roundsnout gurnard, *Lepidotrigla mulhalli*, (c) red gurnard, *Chelidonichthys kumu*, (d) velvet leatherjacket, *Meuschenia scaber* and (e) eastern school whiting, *Sillago flindersi*. The *p*-values from permutation tests assessing for an effect of TL (i.e. catch share was the same for all TLs) are provided, while the shaded areas represent 95 % confidence intervals.

type of work should be given ongoing priority, considering the consistent disproportionate ratio of discarded-to-retained catches by fish trawlers off southeastern Australia.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.fishres.2024.107219.

Data Availability

Data will be made available on request.

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Supplementary material

STable 1. General technical specifications (means ±SE where relevant) for the conventional and low trawls and their rigging used in the study.

Variable	Both trawls	
Steel V-otterboards (kg)	600	
Sweep length (m)	274	
Bridle length (m)	22	
V-wing end (m)	12.4 and 3.7	
Headline length (m)	42	
Ground gear length (m)	34	
Ground-gear extension length (m)	8	
Ground-gear weight (kg)	250	
Ground gear discs Ø (mm)	60 and 130	
Ground gear dropper length (mm)	197	
Total trawl length (m)	63	
Stretched mesh openings (SMO) and twine diameters (mm)		
Frameline reinforcement	141.4 (0.11) and 4.4 (0.04)	
Top wings and anterior body	147.7 (0.20) and 2.5 (0.03)	
Bottom wings and anterior body	114.8 (0.08) and 2.3 (0.02)	
Top and bottom posterior body	97.2 (0.11) and 2.2 (0.02)	
Extension	103.5 (0.16) and 3.5 (0.01)	
Codend	92.8 (0.16) and 7.2 (0.02)	
	Conventional trawl	Low trawl
Floats (200 mm Ø)	50	42
Top and bottom wing side tapers	1N4B and 1N8B	1N1B and B
Anterior body fishing circumference (0.35 × no. of meshes × SMO)	~17.7 m	~13.8 m
Body side tapers	2N2B	1N2B

Ø, diameter; SMO, stretched mesh opening; no., number; N, normal; T, transversals; B, bars

STable 2. List of species (common and Latin names) caught in descending total weights and their numbers (and total length ranges in cm where collected) and percentage (%) weights discarded during 47 deployments of two fish trawls (conventional and low) off Ulladulla, New South Wales, Australia during April and May 2024.

Common name	Latin name	Wt (kg)	Number	% discarded (wt)
Tiger flathead	*Platycephalus richardsoni*	4482.3	12,318 (13.5–58.0)	3.7
Roundsnout gurnard	*Lepidotrigla mulhalli*	3594.2	67,283 (12.0–20.0)	100
Southern fiddler ray	*Trygonorrhina dumerilii*	2722.0	746	100
Greenback stingaree	*Urolophus viridis*	1557.6	3862	100
Smooth stingray	*Bathytoshia brevicaudata*	1375.0	90	100
Common saw shark	*Pristiophorus cirratus*	1291.9	717	8.4
Red gurnard	*Chelidonichthys kumu*	996.1	2317 (21.0–52.5)	0.1
Eastern angel shark	*Squatina albipunctata*	975.0	168	0.1
Velvet leatherjacket	*Meuschenia scaber*	947.3	7205 (13.0–28.5)	100
Australian burrfish	*Allomycterus pilatus*	807.4	1824	100
Grey morwong	*Nemadactylus douglasii*	622.4	2308 (18.0–45.0)	51.0
Sparsely spotted stingaree	*Urolophus paucimaculatus*	538.2	1796	100
Whitespotted skate	*Dentiraja cerva*	510.4	962	100
Yellowback stingaree	*Urolophus sufflavus*	499.6	1095	100
Eastern shovelnose ray	*Aptychotrema rostrata*	483.3	185	11.2
Port Jackson shark	*Heterodontus portusjacksoni*	438.4	395	100
Silver trevally	*Pseudocaranx georgianus*	388.6	995 (25.0–40.0)	0.5
Eastern school whiting	*Sillago flindersi*	388.4	5374 (11.5–28.5)	0.0
Blacktip cucumberfish	*Paraulopus nigripinnis*	297.1	5109 (13.0–25.5)	100
Latchet	*Pterygotrigla polyommata*	294.5	660 (20.5–47.5)	12.7
New Zealand fur seal	*Arctocephalus forsteri*	245.0	3	100
Snapper	*Chrysophrys auratus*	240.5	293 (30.5–55.0)	0.1
Ocean jacket	*Nelusetta ayraudi*	235.9	335	4.7
Cocky gurnard	*Lepidotrigla modesta*	233.2	3494 (11.0–23.5)	100
Redfish	*Centroberyx affinis*	220.2	2313 (10.5–23.5)	44.9
Tasmanian numbfish	*Narcinops tasmaniensis*	219.9	503	100
Southern eagle ray	*Myliobatis tenuicaudatus*	193.8	134	1.6
Bull shark	*Carcharhinus leucas*	170.0	1	0.1
Gemfish	*Rexea solandri*	158.4	226	96.0
Bluestriped goatfish	*Upeneus tragula*	143.1	792 (13.0–31.0)	0.1
Gummy shark	*Mustelus antarcticus*	139.0	46	0.1
Ocean reef perch	*Helicolenus percoides*	131.0	983 (9.0–34.0)	64.4
Melbourne skate	*Spiniraja whitleyi*	115.3	6	30.4

Sandyback stingaree	*Urolophus bucculentus*	113.5	36	0.1
Spotted bigeye	*Priacanthus macracanthus*	111.0	242 (20.0–36.5)	14.5
Peacock skate	*Pavoraja nitida*	107.7	395	100
Common stinkfish	*Foetorepus calauropomus*	105.9	1051	100
Common bellowsfish	*Macroramphosus scolopax*	94.2	7288 (9.5–14.0)	100
Gould's squid	*Nototodarus gouldi*	85.3	215	0.1
Blue mackerel	*Scomber australasicus*	80.8	585 (15.0–23.5)	10.9
John dory	*Zeus faber*	79.0	132 (23.5–44.0)	0.3
Mosaic leatherjacket	*Eubalichthys mosaicus*	68.0	98	5.6
Yellowtail scad	*Trachurus novaezelandiae*	61.4	1041	99.2
Barred grubfish	*Parapercis allporti*	45.7	474 (20.5–27.0)	27.6
Pale octopus	*Octopus pallidus*	45.2	77	0.1
Hermit crab	*Sympagurus* sp.	37.6	158	100
Cuttlefish	*Sepia* spp.	37.0	118	0.8
Bulldog stargazer	*Xenocephalus armatus*	36.6	101	100
Rough golden toadfish	*Lagocephalus lunaris*	35.9	78	100
Hard coral	Na	35.0	28	100
Bluespotted flathead	*Platycephalus caeruleopunctatus*	34.7	53 (40.0–59.0)	15.0
Southern calamari	*Sepioteuthis australis*	32.7	24	0.1
Common stingaree	*Trygonoptera testacea*	32.6	24	100
Silver dory	*Cyttus australis*	32.3	73	0.1
Rusty carpetshark	*Parascyllium ferrugineum*	29.0	26	100
Longfin bigeye	*Cookeolus japonicus*	27.7	113	0.1
Pufferfish	Triodontidae	23.6	136	100
Short-tail torpedo ray	*Tetronarce nobiliana*	22.0	3	100
Blackspot boarfish	*Zanclistius elevatus*	19.5	181	100
Banded wobbegong	*Orectolobus ornatus*	18.0	1	0.1
Eastern smooth boxfish	*Anoplocapros inermis*	17.3	45	100
Australian sardine	*Sardinops neopilchardus*	15.6	1062	100
Painted latchet	*Pterygotrigla andertoni*	14.8	174	98.7
Australian bonito	*Sarda australis*	13.0	0	0.1
Banded stingaree	*Urolophus cruciatus*	12.5	31	100
Pink ling	*Genypterus blacodes*	12.4	13 (48.5–56.0)	0.1
Eastern Australian salmon	*Arripis trutta*	10.2	5	0.1
Mirror dory	*Zenopsis nebulosa*	9.5	20 (32.0–36.5)	32.6
Jackass morwong	*Nemadactylus macropterus*	9.3	39	47.3
Whelks	*Nassarius* sp.	5.7	29	22.8
Starry toadfish	*Arothron firmamentum*	5.4	6	100
Bighead gurnard perch	*Neosebastes pandus*	5.2	13	100
Sea urchin	*Centrostephanus rodgersii*	4.1	20	100
Coffin ray	*Hypnos monopterygius*	4.0	1	100
Mud flathead	*Ambiserrula jugosa*	3.7	50 (28.0–31.0)	100
Giant boarfish	*Paristiopterus labiosus*	3.6	26	100
Spider crab	*Leptomithrax gaimardii*	3.4	17	100
Beaked salmon	*Gonorynchus greyi*	3.0	9	100
Pike eels	*Muraenesox bagio*	2.8	9	100
Flounder	*Pseudorhombus* spp.	2.4	71	100
False bailer shell	*Livonia mammilla*	2.3	3	0.1
Sergeant baker	*Latropiscis purpurissatus*	2.1	9	100
Sponges	Na	1.9	6	100
Elephantfish	*Callorhinchus milii*	1.8	1	100
Flutemouth	*Fistularia* spp.	1.6	2	0.1
Spotted armour gurnard	*Satyrichthys rieffeli*	1.6	8	100
Striped trumpeter	*Latris lineata*	1.5	1	0.1
Miscellaneous teleosts	Na	0.9	486	100
Mulloway	*Argyrosomus japonicus*	0.8	1	0.1
Eastern Balmain bug	*Ibacus peronii*	0.5	3	0.1
Jack mackerel	*Trachurus declivis*	0.4	4	100
Pipefish	*Solegnathus* spp.	0.1	1	100

Na, not applicable; Wt, weight

Appendix 13. Burch, P., Punt, A.E., Tuck, G.N., Knuckey, I., Little, R., Hill, N. and Broadhurst, M.K. 2024. Impacts of changing selectivity on data-rich assessment methods.

Impacts of changing selectivity on data-rich assessment methods

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Abstract

Changes in selectivity that reduce the bycatch of small fish can increase stocks, providing both economic and ecological benefits. However, there is also the potential for biased estimates of stock status from assessment methods that do not account for changes in selectivity. We investigated the potential for such bias in a multi-sector Australian fishery: the southern and eastern scalefish and shark fishery (SESSF). In the late 1990s the SESSF moved from input controls (e.g. restricting fishing gear and effort), to output controls in the form of total allowable catches (TACs), with 34 species groups currently restricted with quota. Stocks in the SESSF are assessed using a tiered approach, with priority species subjected to a 'teir-1' approach, combining catch, length and age composition data with indices of abundance from catch-per-unit-of-effort or surveys and apply a harvest control rule (HCR) to estimate future recommended biological catches (RBCs). The modelling of teir-1 assessments facilitates assessing changes to selectivity on subsequent stocks. A management strategy evaluation (MSE) was used to investigate the impacts of selectivity changes on assessment bias and the subsequent sustainability and economic performance of three SESSF species with different life histories and exploitation characteristics. The results show species-specific benefits in terms of sustainability, albeit with some common costs to production.

Keywords: Fishing mortality; Modelling; Selectivity; Trawl fisheries

1. Introduction

In fisheries, selectivity is defined as a combination of the processes whereby the physical properties of a fishing gear along with the population structure at the time and or location of fishing determine what is caught or escapes, and ultimately the fishing mortality (Millar and Fryer, 1999). In any fishery, selectivity should be optimised for priority target species (i.e. low mortality of immature fish) to support stock sizes, providing both economic and ecological benefits. However, most fisheries are dynamic with variable temporal and/or spatial changes in selectivity among priority species. Ideally, such changes should be incorporated into stock-assessment methods to identify potential impacts for management (Samson, 2014).

One multi-species Australian fishery that has been characterised by considerable variability in temporal selectivity is the 'southern and eastern scalefish and shark fishery (SESSF), which comprises multiple species and methods from ~120 to 155^{o} east and ~30 to 45^{o} south in Australian federal waters (3–200 nm) (Smith and Smith, 2001). The current structure of the SESSF was created by amalgamating separate demersal otter trawl, seine, gillnet, line and trap fisheries, and has been restructured several times since deepwater fishing began in the early 20th century (Grieve and Richardson, 2001). The SESSF is managed using a combination of input controls (e.g. limited entry and fishing gear restrictions) and, since 1998, output controls in the form of total allowable commercial catches (TACs) for 34 target and byproduct species groups (Smith and Smith, 2001).

Stocks in the SESSF are assessed using a tiered approach with generally higher-value species that have better data assessed at a higher-tier level than those with poorer data (Smith et al., 2014; Dowling et al., 2016; Dichmont et al., 2015). So-called 'tier-1 assessments' comprise integrated approaches (Maunder and Punt, 2013), which combine catch and length- and age-composition data with indices of abundance from catch-per-unit-of-effort (CPUE) data or surveys estimating current biomass and exploitation rates, to apply a harvest control rule (HCR) to calculate future recommended biological catches (RBCs). For most relevant SESSF stocks, tier-1 assessments are currently implemented using 'stock synthesis' (Methot and Wetzel 2013). Lower tiers use assessment methods based on either age- or length- composition or only CPUE data. However, the present study focuses on the tier-1 assessments only, because these can account for changes in selectivity by permitting the sub-model of the assessment to temporally vary (i.e. time-blocking, Wilberg et al., 2009), or by creating a new model fleet.

Evaluating different management regimes is typically best done using a simulation process called 'management strategy evaluation' (MSE, Punt et al., 2016). This process involves an 'operating model' (OM) to simulate the stock, the fishery and to generate data which are used by the 'estimation method' (EM) to assess the status of the stock. Outputs from the EM feed into a HCR which sets future RBCs for projected years in the simulation. This process is repeated during sufficient cycles to permit evaluating multiple scenarios.

While improved size selectivity (and lower fishing mortality) will likely benefit SESSF stocks, the impacts on assessments and the subsequent management advice remain unclear. The aims of the current study were to use MSE to investigate the impacts of size-selectivity changes on assessment bias and the subsequent sustainability and economic performance for three SESSF species with different life history and exploitation characteristics. For this purpose, we specify OMs that were loosely based on three SESSF tier-1 stocks exploited along the continental shelf of southeastern Australia: eastern school whiting (*Sillago flindersi*), which is a short-lived species with an assessment plus-group age (the maximum modelled age) of 9 years and natural mortality of M=0.6yr^{-1}; tiger flathead (*Neoplatycephalus rischardsoni*) with a plus-group age of 20 years (M=0.27yr^{-1}); and redfish (*Centroberyx affinis*) with a plus-group age of 40 years (M=0.075yr^{-1}). Specifically, we examine the implications of when: (i) retention and selectivity increase, but the assessment is not concomitantly adjusted; (ii) when the increase in retention and selectivity is accommodated using time-blocking in the assessment; and (iii) when an experiment is used to develop an informative prior for the assessment to account for the change in retention and selectivity.

2. Materials and methods

2.1. Operating model (OM) specification

The existing OM consists of a single-species, age- and length-structured population dynamics structure (Wayte, 2009), and an MSE module that undertakes an assessment using an EM (in this case a tier-1 assessment implemented using stock synthesis version 3.30.15) and then applies HCRs to calculate RBCs and hence TACs. The technical specifications of the SESSF operating model are provided by Wayte (2009). The OM was parameterised using the parameter values in Table 1, which were loosely based on those from the most recent stock assessments of eastern school whiting (Day et al., 2020), tiger flathead (Bessell-Browne, 2022) and redfish (Bessell-Browne and Tuck, 2020).

The OM (and corresponding EM) were simplified to comprise just a single fishing fleet, because having multiple selectivity functions would complicate interpretating the results. Also, redfish is currently assessed to be at only 3% of unfished spawning biomass (Bessell-Browne and Tuck, 2020) making evaluation of harvest strategy performance challenging and comparisons with the other stocks problematic. Therefore, for the purposes of modelling here, the unfished recruitment and historical catches of redfish were adjusted so that each stock was around the target reference point of 48% unfished spawning biomass at the beginning of the projection period in 2021.

2.2. Estimation method (EM)

The tier-1 EM for the three stocks were pre-specified to match the parameters and assumptions within the OM, except for selectivity, which was mis-specified in the EM for some scenarios. All three tier-1 EMs involved a von Bertalanffy growth function, mean unfished recruitment (R_0), estimated recruitment deviations and a single CPUE fleet with logistic retention and selectivity ogives. We assumed growth and natural mortality for all three species were time-invariant (Table 1).

2.3. Simulation scenarios

Logistic selectivity and retention ogives were modified within the OM and the EM, depending on the scenario evaluated. The initial and modified selectivity and retention parameters used in this study are shown in Table 2 and the ogives are shown in Figure 1. The retention and selectivity inflection parameters of eastern school whiting and redfish were increased by 2 cm, while tiger flathead was increased by 3 cm (Table 2). These values were selected to provide sufficiently large changes in retention and selectivity to impact the stock. The CVs and sample sizes used in the data generation module are provided in Table S1.

To simulate the objective of reducing unwanted fishing mortality (i.e. of discards) by modifying trawl codends (including larger diamond-mesh and/or square-mesh panels) to allow small fish to escape, selectivity was assumed to be right shifted (i.e. only scenarios where fewer small fish are retained were considered). Two general cases of modified selectivity curves were considered: (i) retention does not change, but discards reduce; and (ii) selectivity of both the retained and discarded components change.

Within the above cases, three main questions were evaluated.

1. For cases (i) and (ii), what are:
    a) the impacts on the stock when the assessment assumes selectivity is time invariant (i.e., no time-blocking), compared to,
    b) an assessment where selectivity is time-blocked four years after the change in selectivity?
2) For (i) above, what is the benefit of undertaking an experiment to estimate the modified selectivity? The experiment would be implemented as a survey within the assessment and provide unbiased selectivity estimates immediately after the change in selectivity.
3) Because growth estimation can be sensitive to the absence of small/young fish, how is the estimation of growth within the assessment impacted by the change in selectivity?

Seven scenarios were undertaken to evaluate these questions (Table 3). For each stock, the OM was projected for 40 years. The SESSF has adopted a 4-year period between assessments from 2024 onwards (pers. com. Daniel Corrie, AFMA), and so the right shifting of retention and selectivity ogives were implemented in the OM four years before the end of the historical period (i.e. in 2016). The first assessment was undertaken using the EM (Stock Synthesis) in 2021 (the end of the first projection year) and every four years subsequently for the 40 years of the projection (until 2060). The RBC in each year of the simulation was set based on the HCR from the most recent application of the EM.

2.4. Harvest control rule

The SESSF tier-1 HCR specifies target and limit biomass reference points along with a target fishing mortality rate (F) to determine the RBC for each tier-1 stock in the SESSF quota management system (Fig. S1). Current default limit (SB_{lim}), break (SB_{break}) and target (SB_{targ}) reference points were set in 2009 by the Australian Fisheries Management Authority (AFMA), who manage and regulate Commonwealth fisheries. The term SB_{lim} represents the limit reference point (LRP) of 20% unfished spawning biomass, while SB_{break} is the stock status at which the fishing mortality used to calculate the RBC is reduced below F_{targ} (i.e. the break point in the HCR) and was set to 35% unfished spawning biomass. The default target reference point (TRP; SB_{targ}) of 48% of unfished spawning biomass corresponds to the economic target for B_{MEY} (the biomass corresponding to maximum economic yield) in the SESSF (Smith et al., 2008; 2014). While the actual management advice for tiger flathead (Bessell-Browne, 2022) uses a SB_{MEY} of 40% unfished biomass, based on an economic analysis (Klaer 2010), for consistency among species, we used a TRP of 48% for all three stocks in this study.

2.5. Performance measures

The results are based on 100 simulations of a 40-year projection period in which RBCs were updated every four years. The performance of each management strategy was evaluated in terms of the following measures:

- probability of the OM spawning biomass (SB) dropping below the LRP at least once during the 40-year projection period (a proxy for 'functional ecological extinction'). This probability is assessed against a 10% threshold level, which is the risk tolerance specified in the 'fishery harvest strategy policy' of the Australian Commonwealth government (CFHSP, Department of Agriculture and Water Resources, 2018);
- probability of a zero RBC, representing the likelihood of the fishery being closed;
- boxplots and tables showing medians, interquartile ranges and ranges of values over the 100 simulations for the annual average interannual variation (AAV) in catches over the 40-year projection period, where AAV is defined as:

$$AAV = \sum_{y=1}^{y=40} \left|\tilde{C}_y - \tilde{C}_{y-1}\right| / \sum_{y=1}^{y=40} \tilde{C}_{y-1}$$

  where $\tilde{C}_y$ is the catch during year y; $y = 1$ is the start of the projection period; $y = 40$ is the end of the projection period;

- boxplots and tables showing median, interquartile range and range of values over the 100 simulations for the total average catch over the 40-year projection period; and
- bias between the OM and the EM was assessed using the relative error of SB_0, SB and depletion (SB/SB_0), where relative error for a quantity x, at year y is calculated as:

$$RE_{x,y} = \frac{EM_{x,y} - OM_{x,y}}{OM_{x,y}}.$$

3. Results and Discussion

3.1. Eastern school whiting

For eastern school whiting, increasing the length-at-50%-retention within the OM (scenario B) slightly reduced the probability of the stock falling below the limit reference point (Pr(SB<LRP)) during the projection period from 0.166 to 0.141 (Table 4, Fig. 2). Similarly, the probability of a zero RBC (Pr(RBC=0)) was slightly reduced, from 0.002 to 0.001. Average catches under scenario B were ~195 t p.a.

lower than the base case, and the average catch variation (AAV) increased from 0.012 to 0.023. Stock status in the OM was slightly higher under scenario B (Fig. 3) and the level of bias between the OM and EM was similar (Fig. 4). When the change in retention was accommodated within the EM using a time-block (scenario C), Pr(*SB*<LRP) and Pr(RBC=0) increased to 0.165 and 0.003 respectively (Table 3, Fig. 3).

When both retention and selectivity were increased in the OM, but this was ignored when conducting assessments (scenario D), Pr(*SB*<LRP) and Pr(RBC=0) decreased to 0 and 0.002, respectively (the equal lowest level among the seven scenarios). However, this decrease was at the cost of lower catches (Table 4, Fig. 2). The *SB* in OM was well above the TRP (Fig. 3), while the level of bias in depletion between the OM and the EM was higher compared with the base case (Fig. 4). When the change in retention and selectivity was accommodated with time-blocking in the EM (scenario E), the Pr(*SB*<LRP) and Pr(RBC=0) remained at the equal lowest level, while the average catch increased and the AAV reduced (Table 4, Fig. 2). Scenario E maintained the stock just above the TRP over the entire projection period and had the lowest level of bias between the OM and EM (Figs 3 and 4).

Using a prior (derived from an experimental survey) to accommodate for the change in retention (scenario F) resulted in the highest Pr(*SB*<LRP) and Pr(RBC=0), while average catches were ~80 t p.a. lower than the base case (Table 4, Fig. 2). The median stock status tracked the break point of the HCR over the projection period (Fig. 3). When priors were used to accommodate for the change in retention (scenario G) the performance was almost identical to scenario E, the equivalent scenario without priors, suggesting the impacts of the priors were negligible, which requires further investigation.

3.2. Tiger flathead

Similar to eastern school whiting, increasing the length at 50% retention within the OM (scenario B) for tiger flathead resulted in small reduction in Pr(*SB*<LRP), from 0.017 to 0.010 and Pr(RBC=0), from 0.006 to 0.004 (Table 4, Fig. 5). However, average catches under scenario B were ~230 t p.a. lower than the base case and AAV increased from 0.008 to 0.018. When the change in retention was accommodated within the EM using a time-block (scenario C), Pr(*SB*<LRP) increased to 0.015 and Pr(RBC=0) remained at 0.004 (Table 4, Fig. 5).

When both retention and selectivity were increased in the OM (scenario D), Pr(*SB*<LRP) and Pr(RBC=0) their lowest levels among the seven scenarios; but, as observed with eastern school whiting, average catches were also the lowest among the scenarios (Table 4, Fig. 5). When the change in retention and selectivity was accommodated with time-blocking in the EM (scenario E), the Pr(*SB*<LRP) and Pr(RBC=0) increased compared with scenario D but remained lower than the basecase, while the average catch and AAV both increased (Table 4, Fig. 5).

Using a prior (scenario F) resulted in the second highest Pr(*SB*<LRP) and Pr(RBC=0), while the average catches were ~130 t p.a. lower than the base case (Table 4, Fig. 5). When priors were used to accommodate for the change in retention and selectivity (scenario G) the performance was very similar to scenario E, the equivalent scenario without priors. The similarities between scenarios E and G were also present for eastern school whiting. Scenario D, where retention and selectivity increase in the OM but not the EM showed a relatively high level of bias between the OM and the EM estimates of current SSB and stock status (Figs 6 and 7).

3.3. Redfish

For redfish, when retention was increased within the OM (scenario B) there was a small reduction in sustainability with Pr(*SB*<LRP) increasing from 0.006 to 0.011 while Pr(RBC=0) remained at zero (Table 4, Fig. 8). As for the other species, improved sustainability resulted in a slight reduction in average catch. Stock status in the OM was around the target for the entire projection period, and very similar to the base-case scenario, while the bias between the OM and the EM was slightly lower (Figs 9 and 10). When the change in retention was accommodated within the EM using a time-block (scenario C), Pr(*SB*<LRP) and Pr(RBC=0) increased slightly to 0.012 and 0.008 respectively with average catches ~80 t p.a. higher (Table 4, Fig. 8). Bias between the OM and the EM steadily increased over the projection period with the OM stock status

declining to the break point of the HCR at the of the projection period while the EM stock status remained at the target (Figs 9 and 10).

When both retention and selectivity were increased in the OM (scenario D), Pr(RBC=0) increased slightly to 0.016, while Pr(*SB*<LRP) remained at zero (Table 4, Fig. 8). Average catches were also ~70 t p.a. lower, compared with the base case and AAV was higher at 0.010. When the change in retention and selectivity was accommodated with time-blocking in the EM (scenario E), the Pr(RBC=0) decreased compared with scenario D, while Pr(*SB*<LRP) remained at zero. The average catch was ~35 t p.a. higher than the base case with AAV at 0.006 (Table 4, Fig. 8).

When a prior was used to accommodate the change in retention (scenario F), Pr(*SB*<LRP) and Pr(RBC=0) increased to ~2%, while average catches were 720 t p.a, and the highest of all scenarios (Table 4, Fig. 8). When priors were used to accommodate for the change in retention and selectivity (scenario G) the performance was similar to scenario E, however, catches were ~50 t p.a. lower.

3.4. Conclusions

Within the assumptions provided, it is clear there would be benefits to stocks of all three species associated with subtle changes to gear selectivity; albeit with some caveats in terms of production. Specifically, for all three stocks, increasing the retention within the OM (scenario B) slightly improved sustainability, but at the cost of slightly reduced catches. When retention was also time-blocked in the EM (scenario C), sustainability the probability of falling below the LRP increased for all species, while catches increased for eastern school whiting and redfish. Adding a prior (based on an experimental survey) to the EM (scenario F) resulted in higher catches for all stocks with small changes in sustainability measures, although the direction of change was not consistent among stocks.

When both retention and selectivity were increased in the OM (scenario D), sustainability improved for all stocks except for redfish where Pr(*SB*<LRP) remained at zero and Pr(RBC=0) increased slightly. All stocks underwent declines in catches and increases in AAV. When retention and selectivity were time-blocked in the EM (scenario E), catches increased for all stocks and the risk to sustainability either remained the same or declined slightly for eastern school whiting and redfish, but increased for tiger flathead. While the prior provided higher catches and similar sustainability measures for retention, adding a prior for both retention and selectivity (scenario G) had no or minimal impact for eastern school whiting and tiger flathead, with higher catches and increased risk to sustainability for redfish. For redfish there was very little contrast among the scenarios compared to the other stocks and this warrants further investigation, although this outcome probably reflects their current status of being overfished.

The outcomes of the modelling approaches here also reiterate challenges for maximising the selectivity of individuals species within a multi-species (and gear) fishery. There are similarities in the sizes and body shapes among most target, byproduct and bycatch species in the SESSF which mostly preclude investigating modifications to trawls that will satisfy outcomes for all species. For every reduction in bycatch and fishing mortality of one species, there is likely to be at least some compensatory loss of retained catches. These characteristics means some species will need to be prioritized over others; decisions that are probably best made concerning not only economic value but also life-history strategies.

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Table 1. Pre-specified biological parameters for the three stocks used in the operating model.

Pre-specified parameters	Eastern school whiting	Tiger flathead		Redfish	
Plus-group age (years)	9	20		40	
Recruitment steepness, (h)	0.75	0.75		0.75	
Natural mortality, (M)	0.6	0.27		0.075	
Unfished recruitment, R_0	183,320	22,741		68,000	
Recruitment variability, s_R	0.7	0.7		0.7	
Maturity logistic inflection	16	30		19	
Maturity logistic slope	2	0.25		6	
Sex	Sex aggregated	Female	Male	Female	Male
Von Bertalanffy, K (yr^{-1})	0.25	0.174	0.151	0.250	
Length (Age 0, cm)	6.83	28.6	26.9	13.6	13.8
Length (Max Age, cm)	25.68	55.9	45.7	25.4	23.7
Length-weight scale, a	0.0000132	0.00000588		0.0000057	
Length-weight power, b	2.93	3.31		2.77	
Length at age coefficient of variation	0.090	0.114		0.120	
Pre-specified operating model recruitment deviations	1981–2015	1915–2017		1975–2000	

Table 2. Selectivity and retention parameters (cm) for the logistic ogives used for the three stocks used in the operating model.

	Eastern school whiting		**Tiger flathead**		**Redfish**	
Parameter	**Inflection**	**Slope**	**Inflection**	**Slope**	**Inflection**	**Slope**
Retention original	15.20	1.34	31.29	1.41	12.30	1.83
Retention modified	17.20	1.34	34.29	1.41	14.30	1.83
Selectivity original	17.59	3.00	35.31	2.24	19.47	0.93
Selectivity modified	19.59	3.00	38.31	2.24	21.47	0.93

Table 3. Details of the seven scenarios evaluated in this study, the question the evaluate (from above) and how they are implemented within the management strategy evaluation.

Scenario	**Details**	**Question evaluated**	**Implementation**
A	No change in retention or selectivity in either the OM or EM (base case).	Na	Na
B	Retention increases in the OM but not the EM.	1a (i)	Retention is right-shifted using a time-block in the OM. The EM assumes retention is unchanged.
C	Retention increases in both the OM and the EM.	1b (i)	Retention is right-shifted using a time-block in both the OM and the EM.
D	Retention and selectivity increase in the OM but not the EM.	1a (ii)	Retention and selectivity are right-shifted using a time-block in the OM. The EM assumes retention and selectivity are unchanged.
E	Retention and selectivity increase in both the OM and the EM.	1b (ii)	Retention and selectivity are right-shifted using a time-block in both the OM and the EM.
F	Retention increases in the OM and there is an 'experimental survey' that provides a prior for the new retention in the EM.	2 (i)	Scenario B, with the addition of a prior[1] based on the new retention is added to the EM.
G	Retention and selectivity increases in the OM and there is an 'experimental survey' that provides a prior for the new retention and selectivity curves in the EM.	2 (ii)	Scenario D with the addition of priors[1] based on the new retention and selectivity are added to the EM.

OM, operating model; EM, estimation method; Na, not applicable

[1] A normal prior with mean equal to the modified retention/selectivity and a standard deviation of 0.1 was used.

Table 4. Summary statistics for the seven scenarios for eastern school whiting, tiger flathead and redfish: median average catch (t), median annual average catch variation (AAV), the probability of a 0 t RBC (Pr(RBC=0)), the percentage probability of the operating model (OM) stock biomass (SB) falling below the limit reference point (Pr(SSB<LRP)).

	Scenario						
Performance measure	**A**	**B**	**C**	**D**	**E**	**F**	**G**
Eastern school whiting							
Average catch	1098.9	903.05	937.1	837.05	1010	940.35	1009.95
AAV	0.012	0.023	0.013	0.038	0.014	0.014	0.014
Pr(RBC=0)	0.002	0.001	0.003	0.000	0.000	0.003	0.000
Pr(SB<SBlim)	0.166	0.141	0.165	0.002	0.002	0.167	0.002
Tiger flathead							
Average catch	2869.3	2635.25	2736.15	2111.55	2991.2	2737.7	2983.2
AAV	0.008	0.018	0.009	0.110	0.007	0.008	0.006
Pr(RBC=0)	0.006	0.004	0.004	0.004	0.004	0.008	0.004
Pr(SB<SBlim)	0.017	0.010	0.015	0.000	0.016	0.014	0.015
Redfish							
Average catch	585.5	582.5	662.55	514	620.2	720.6	673.6
AAV	0.004	0.003	0.003	0.010	0.006	0.005	0.043
Pr(RBC=0)	0.006	0.011	0.012	0.016	0.006	0.021	0.015
Pr(SB<SBlim)	0.000	0.000	0.008	0.000	0.000	0.015	0.026

Captions to figs

Figure 1. The retention (blue) and selectivity (red) ogives for eastern school whiting (top), tiger flathead (middle) and redfish (bottom). Solid lines show the retention and selectivity ogives from the first year to 2015, dashed lines show the modified retention and selectivity from 2016 onwards.

Figure 2. Summary statistics for eastern school whiting for scenarios A–G: (a) the probability of the OM spawning stock biomass falling below the limit reference point, (b) the probability of a 0 t RBC, (c) boxplots of the annual average variation in catches (AAV), and (d) boxplots of annual catches. The bar plots show probabilities, while the box and whisker plots show the medians as the middle lines, the 25th and 75th percentiles as the tops and bottoms of the boxes, the whiskers show the full range of the values, and the points are potential outliers in the distribution.

Figure 3. Eastern school whiting stock status for scenarios A–G, with medians (lines) and 90% simulation intervals from the OM (light grey shaded area) and the EM (dark grey shaded area). The vertical grey dashed lines show the start of the 40-year projection period. The green dashed lines are the target reference point, the dashed orange lines are the breakpoint of the harvest control rule, the red dashed lines are the limit reference point.

Figure 4. Relative error distributions by year over the projection period for initial spawning biomass (top), current spawning biomass (middle) and current stock status (bottom) for eastern school whiting scenarios A–G. The black line represents the median over 100 simulations and the shaded area the 90% simulation intervals.

Figure 5. Summary statistics for tiger flathead for scenarios A–G: (a) the probability of the OM spawning stock biomass falling below the limit reference point, (b) the probability of a 0 t RBC, (c) boxplots of the annual average variation in catches (AAV), and (d) boxplots of annual catches. The bar plots show probabilities, while the box and whisker plots show the medians as the middle lines, the 25th and 75th percentiles as the tops and bottoms of the boxes, the whiskers show the full range of the values, and the points are potential outliers in the distribution.

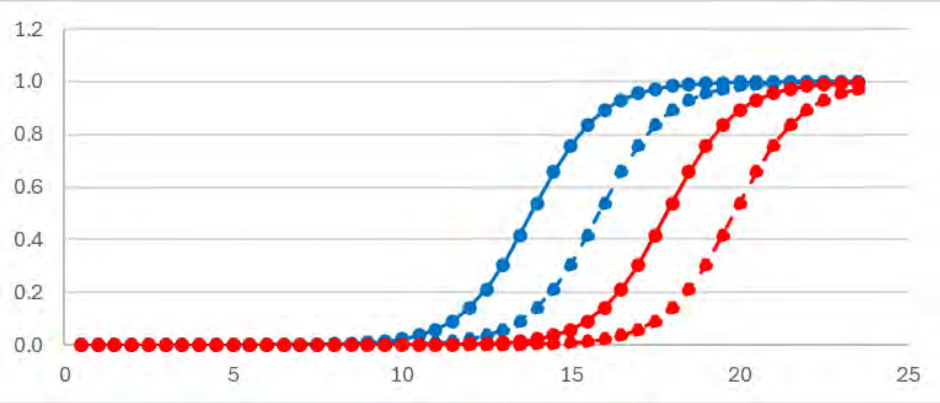
Figure 6. Tiger flathead stock status for scenarios A–G, with medians (lines) and 90% simulation intervals from the OM (light grey shaded area) and the EM (dark grey shaded area). The vertical grey dashed lines show the start of the 40-year projection period. The green dashed lines are the target reference point, the dashed orange lines are the breakpoint of the harvest control rule, the red dashed lines are the limit reference point.

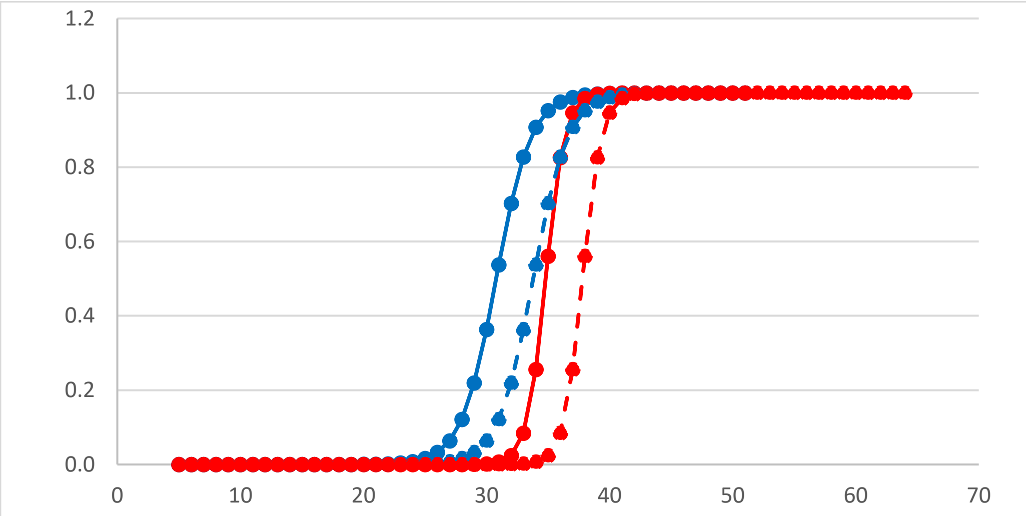
Figure 7. Relative error by year over the projection period for initial spawning biomass (top), current spawning biomass (middle) and current stock status (bottom) for tiger flathead scenarios A–G. The black line represents the median over 100 simulations and the shaded area the 90% simulation intervals.

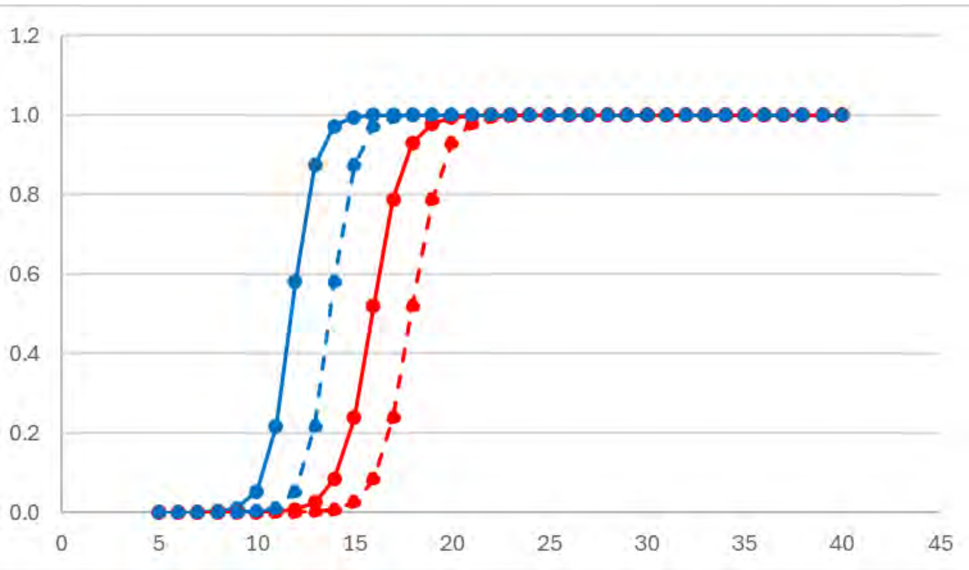
Figure 8. Summary statistics for redfish for scenarios A–G: (a) the probability of the OM spawning stock biomass falling below the limit reference point, (b) the probability of a 0 t RBC, (c) boxplots of the annual average variation in catches (AAV), and (d) boxplots of annual catches. The bar plots show probabilities, while the box and whisker plots show the medians as the middle lines, the 25th and 75th percentiles as the tops and bottoms of the boxes, the whiskers show the full range of the values, and the points are potential outliers in the distribution.

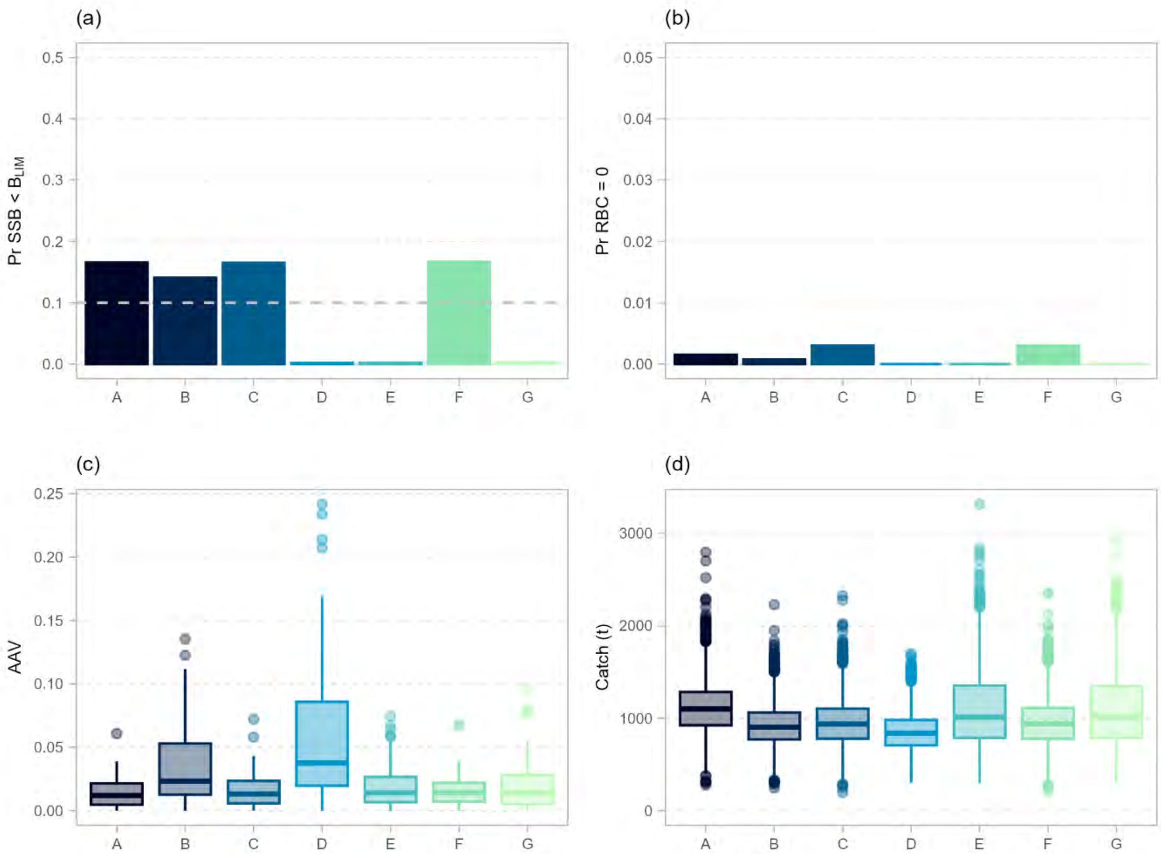
Figure 9. Redfish stock status for scenarios A–G, with medians (lines) and 90% simulation intervals from the OM (light grey shaded area) and the EM (dark grey shaded area). The green dashed lines are the target reference point, the dashed orange lines are the breakpoint of the harvest control rule, the red dashed lines are the limit reference point.

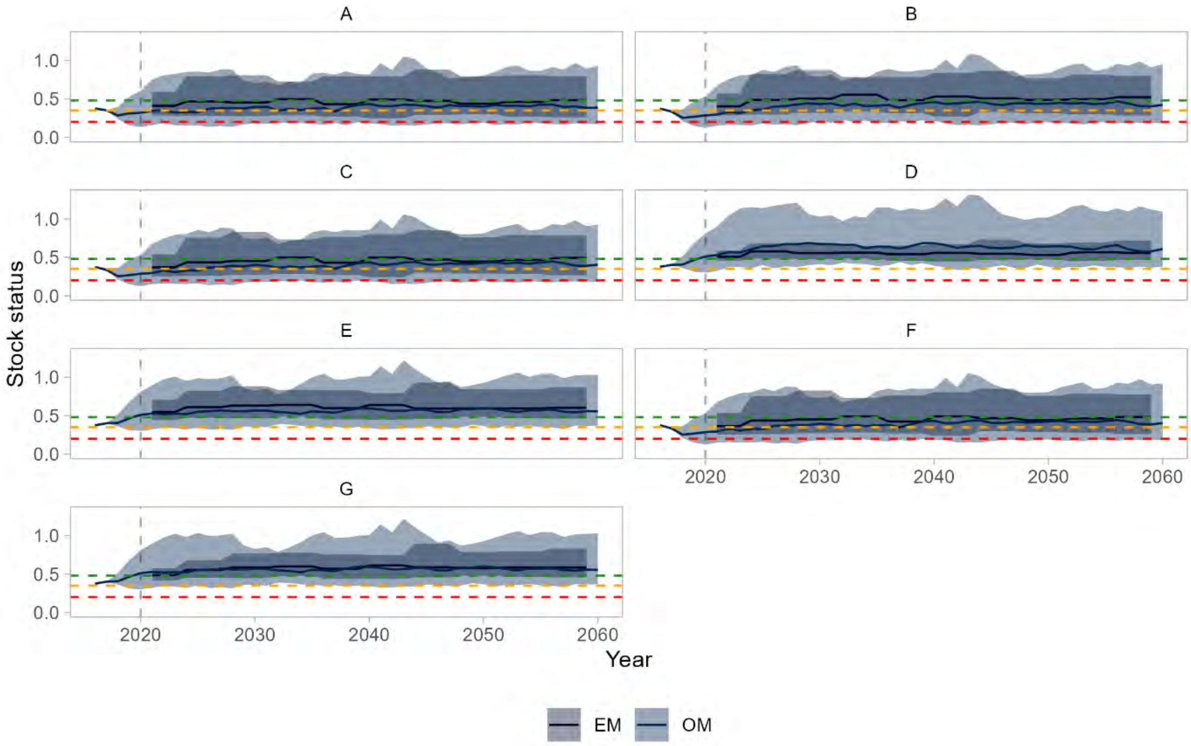
Figure 10. Relative error by year over the projection period for initial spawning biomass (top), current spawning biomass (middle) and current stock status (bottom) for redfish scenarios A–G. The black line represents the median over 100 simulations and the shaded area the 90% simulation intervals.

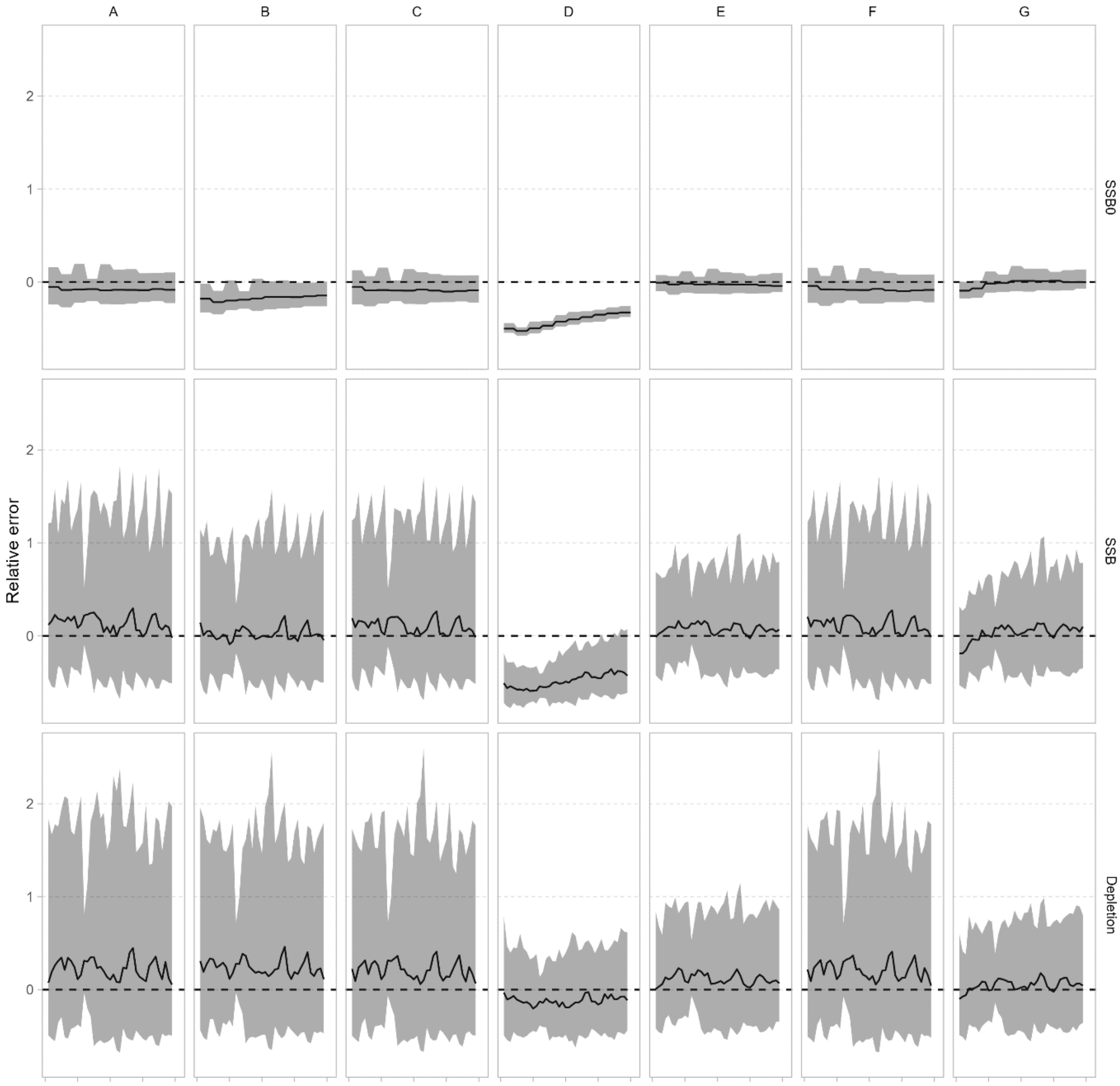

1.2
1.0
0.8
0.6
0.4
0.2
0.0
0
5
10
15
20
25

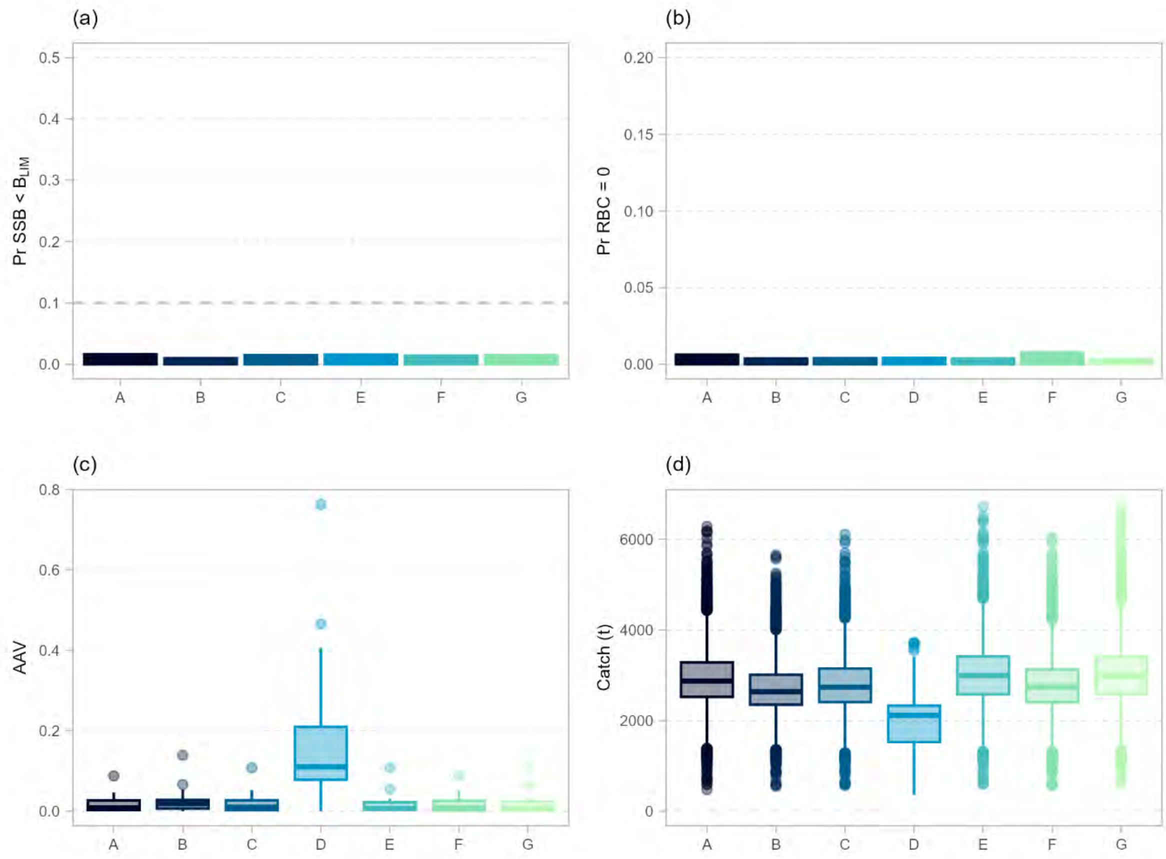

1.2
1.0
0.8
0.6
0.4
0.2
0.0
0
10
20
30
40
50
60
70

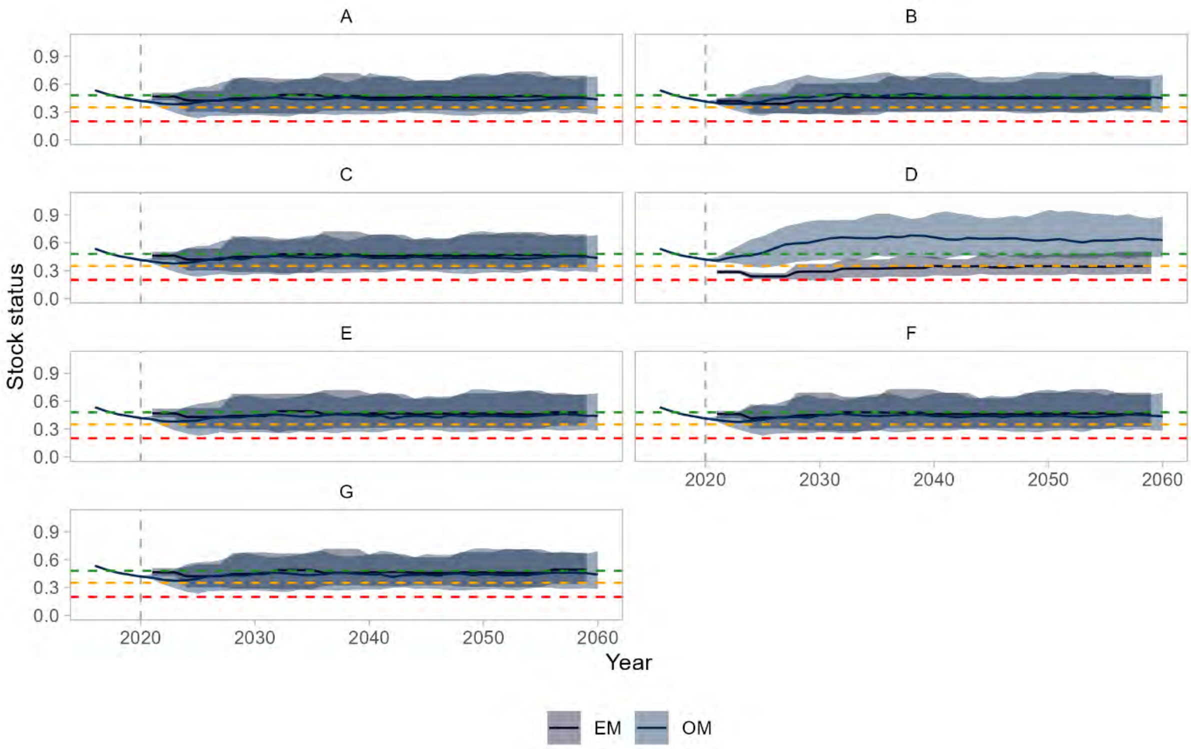

1.2
1.0
0.8
0.6
0.4
0.2
0.0
0
5
10
15
20
25
30
35
40
45

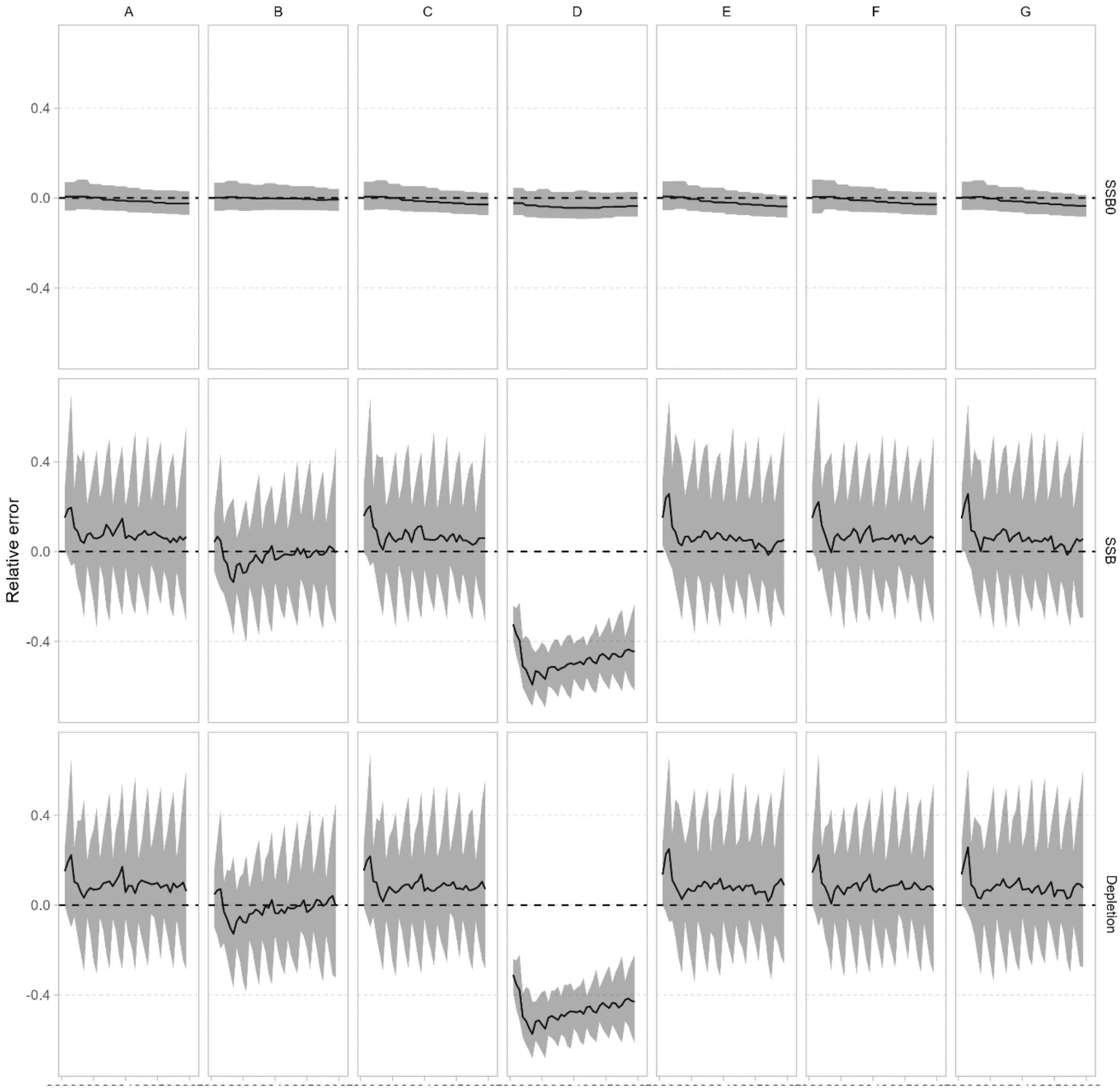

(a)
Pr SSB < B_LIM
0.5
0.4
0.3
0.2
0.1
0.0
A
B
C
D
E
F
G
(b)
Pr RBC = 0
0.05
0.04
0.03
0.02
0.01
0.00
A
B
C
D
E
F
G
(c)
AAV
0.25
0.20
0.15
0.10
0.05
0.00
A
B
C
D
E
F
G
(d)
Catch (t)
3000
2000
1000
0
A
B
C
D
E
F
G


A
B
C
D
E
F
G
Stock status
1.0
0.5
0.0
2020
2030
2040
2050
2060
Year
EM
OM

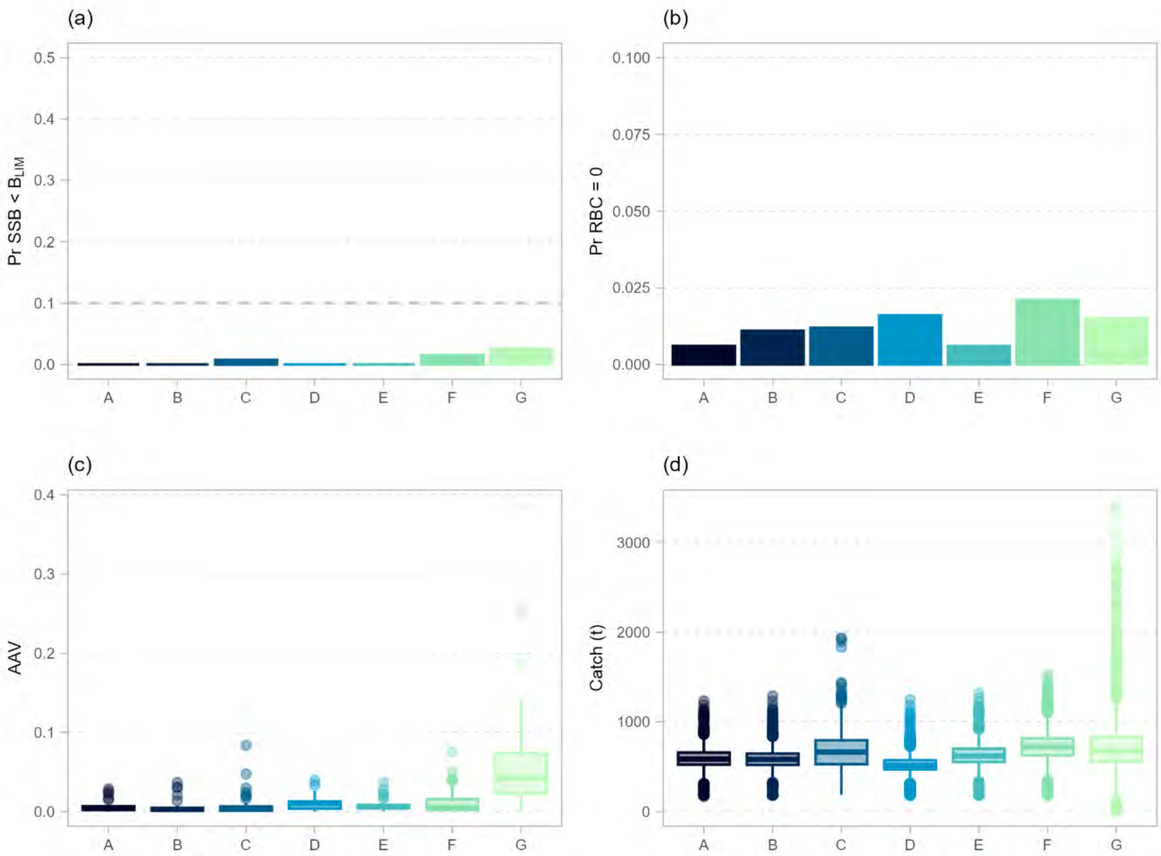

A
B
C
D
E
F
G
SSB0
SSB
Depletion
Relative error
2
1
0

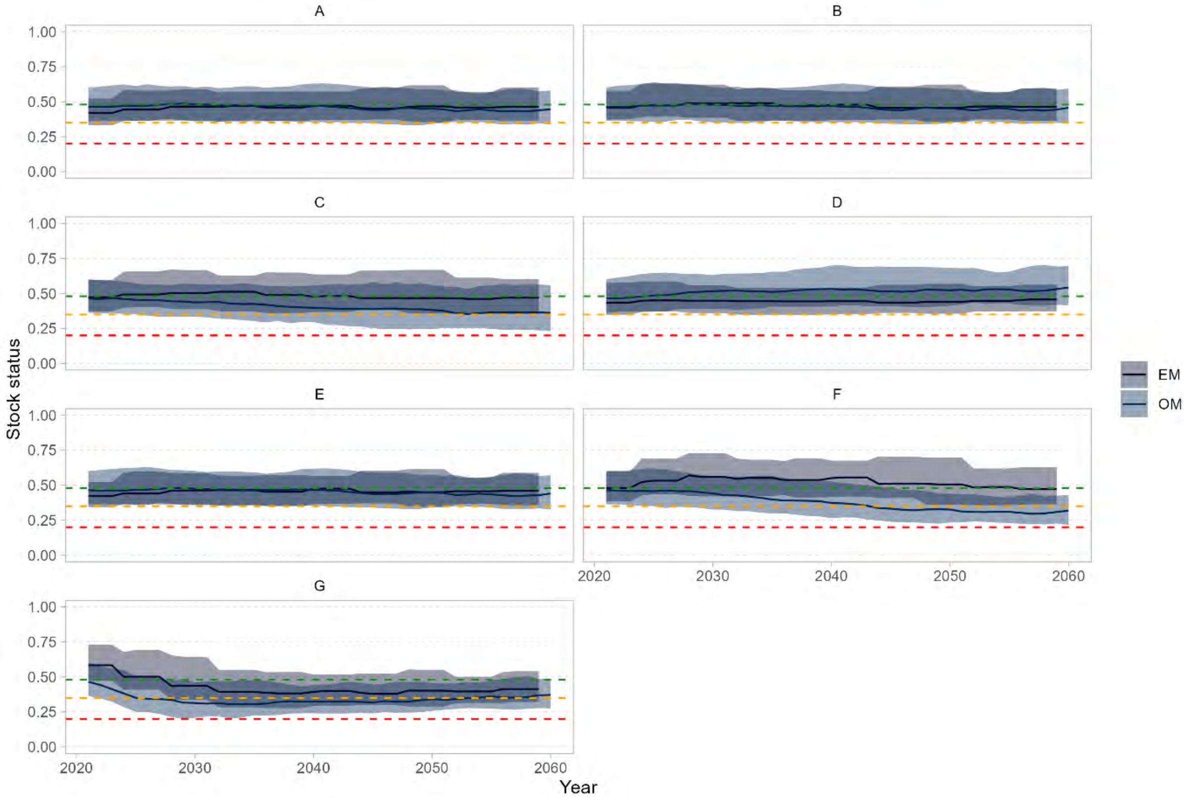

(a)
Pr SSB < B_{LIM}
0.5
0.4
0.3
0.2
0.1
0.0
A
B
C
E
F
G
(b)
Pr RBC = 0
0.20
0.15
0.10
0.05
0.00
A
B
C
D
E
F
G
(c)
AAV
0.8
0.6
0.4
0.2
0.0
A
B
C
D
E
F
G
(d)
Catch (t)
6000
4000
2000
0
A
B
C
D
E
F
G


A
B
C
D
E
F
G
0.9
0.6
0.3
0.0
Stock status
2020
2030
2040
2050
2060
Year
EM
OM


A
B
C
D
E
F
G
0.4
0.0
-0.4
SSB0
SSB
Depletion
Relative error

.


(a)
Pr SSB < B_LIM
0.5
0.4
0.3
0.2
0.1
0.0
A B C D E F G
(b)
Pr RBC = 0
0.100
0.075
0.050
0.025
0.000
A B C D E F G
(c)
AAV
0.4
0.3
0.2
0.1
0.0
A B C D E F G
(d)
Catch (t)
3000
2000
1000
0
A B C D E F G


A
B
C
D
E
F
G
Stock status
Year
EM
OM
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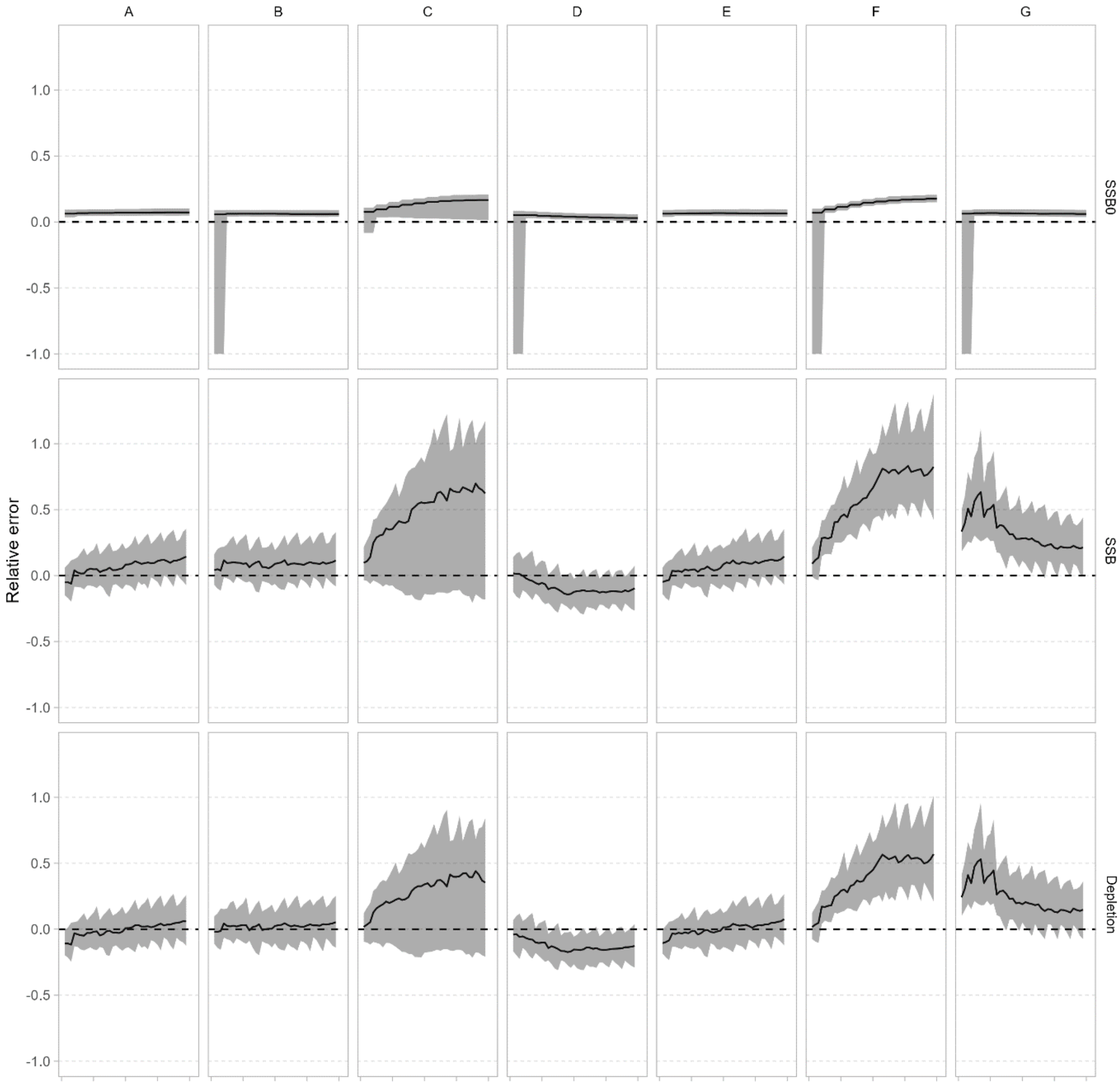
0.75
0.50
0.25
0.00
2020
2030
2040
2050
2060


A
B
C
D
E
F
G
SSB0
SSB
Depletion
Relative error
1.0
0.5
0.0
-0.5
-1.0

Supplementary Material 1: Additional tables and figures

Table S1. Years the data sources are included, coefficients of variation (CV) and effective sample sizes for the operating models. CPUE, catch per unit of effort.

Data and assessment characteristics	**Eastern school whiting**	**Tiger flathead**	**Redfish**
Catch	1947–2020	1915–2020	1975–2020
CPUE	1986–2020	1915–2020	1975–2020
CPUE CV	0.218	0.1	0.21
Length (retained and discard) and conditional-age-at-length	yes	yes	yes
Discards (CV)	yes (0.25)	yes (0.15)	yes (0.15)
Effective sample size length retained	100	100	200
Effective sample size length discarded	50	50	50
Effective sample size conditional age-at-length retained	100	100	250
Recruitment deviations	1981–2015	1971–2017	1975–2000

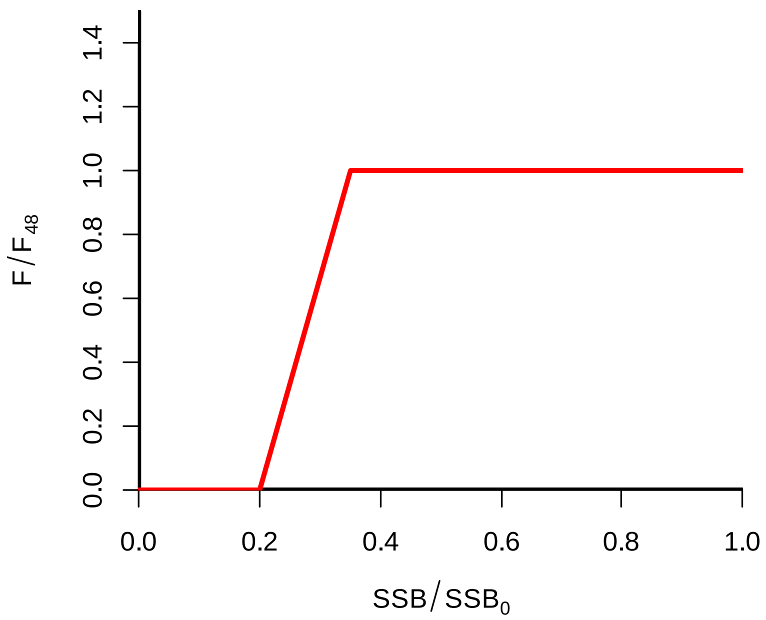
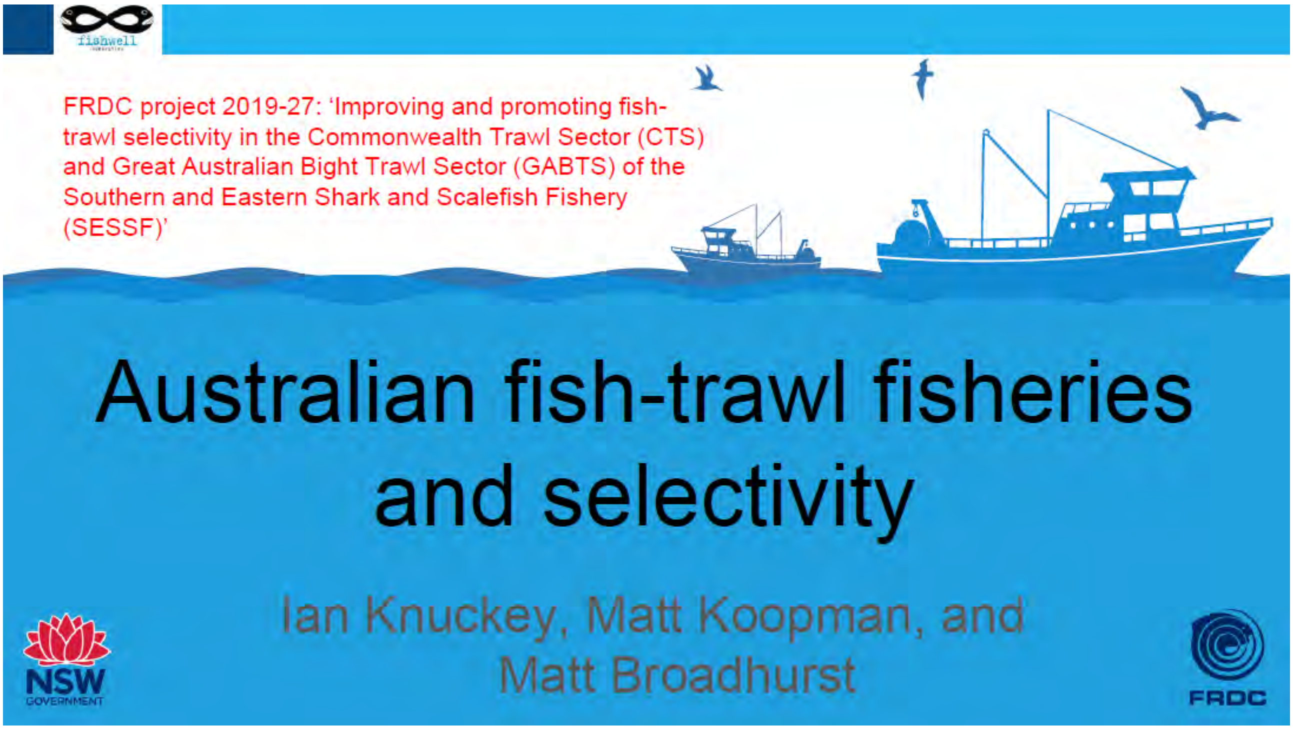


Figure S1. The 20:35:48 harvest control rule used for the eastern school whiting, tiger flathead and redfish in this study. F_{48} is the fully-selected fishing mortality that is estimated to maintain the spawning biomass at 48% of its unfished level.

Appendix 14. Industry presentation of national review of modifications to improve selection in fish trawls.



Australian fish-trawl fisheries

- Seven separate Commonwealth fisheries
  - Southern and Eastern Scalefish and Shark Fishery:
    - Commonwealth Trawl Sector (Danish seine and otter trawl, 30,000 t and GVP ~$42 m)
    - Great Australian Bight Trawl Sector (1,500 t and GVP ~$9 m)
    - East Coast Deepwater Trawl (sporadic fishing)
  - Heard and McDonald Islands (mainly longline now)
  - Macquarie Island (mainly longline now)
  - Western Deepwater Trawl Fishery (limited fishing)
  - North West Coast Trawl Fishery (limited fishing – mainly Scampi)

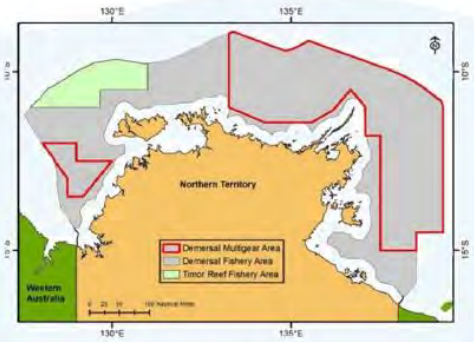
Australian fish-trawl fisheries

- Seven state fisheries:
  - Northern Territory Demersal Trawl and Timor Reef
  - Northern Territory Timor Reef Fishery
  - Queensland Fin Fish (stout whiting) Trawl Fishery
  - Queensland Gulf of Carpentaria Developmental Fin Fish Trawl Fishery
  - New South Wales Fish (Northern and Southern) Trawl Fishery
  - Victorian Inshore Trawl (but mainly prawn)
  - Western Australian Pilbara Fish Trawl (interim) Managed Fishery

Australian fish-trawl fisheries

- Northern Territory Demersal Trawl and Timor Reef
  - Demersal trawl targets:
    - goldband snapper; and
    - red snappers

  - Trawl bycatch / selectivity:
    - trawl mesh ≥110 mm;
    - prohibition on double codend liner;
    - footline weight ≤4 kg per lineal meter; and
    - mesh ≤ 90 ply x 400 denier.



Fish drawings: FAO and Rosalind Poole

Australian fish-trawl fisheries

- Queensland Gulf of Carpentaria Developmental Fin Fish Trawl
  - Catch ~500 t max (0 now), GVP N/A and 2 licences
  - Demersal trawl targets:
    - Tropical snappers (crimson and saddletail)
  - Trawl bycatch / selectivity:
    - minimum mesh size;
    - maximum ground gear weight;
    - mandatory TED; and
    - BRDs.

Fish drawings: FAO and Rosalind Poole

Australian fish-trawl fisheries

- Queensland Fin Fish (stout whiting) Trawl Fishery
  - Catch ~1000 t, GVP $2.1 m and 2 active licences
  - Danish seine and otter trawls target:
    - stout Whiting and 

      (with yellowtail scad and goatfish as byproducts)
  - Trawl bycatch / selectivity:
    - $\geq$38- and $\leq$100-mm mesh;
    - net length $\leq$ 80 m, with OT sweeps $\leq$ 128 m; and
    - mandatory TED.

Fish drawings: FAO and Rosalind Poole

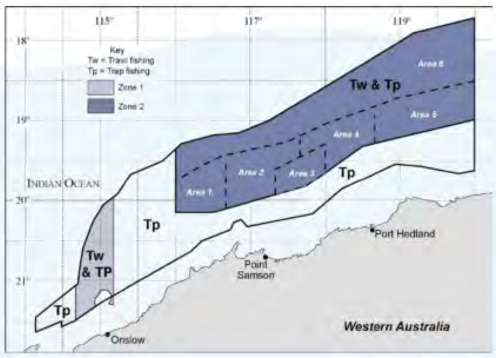
Australian fish-trawl fisheries

- NSW Fish (Northern and Southern) Trawl Fishery
  - Catch ~1000 t, GVP ~\$6 million and ~56 licences (60% north)
  - Demersal trawl targets:
    - stout whiting;  redspot whiting; and
    - flatheads;  
    - silver trevally; royal red prawns
  - Trawl bycatch / selectivity:
    - significant input controls;
    - mesh size ≥90 mm;
    - bobbin gear prohibited north of 32 degrees; and
    - BRDs required.

Fish drawings: FAO and Rosalind Poole

Australian fish-trawl fisheries

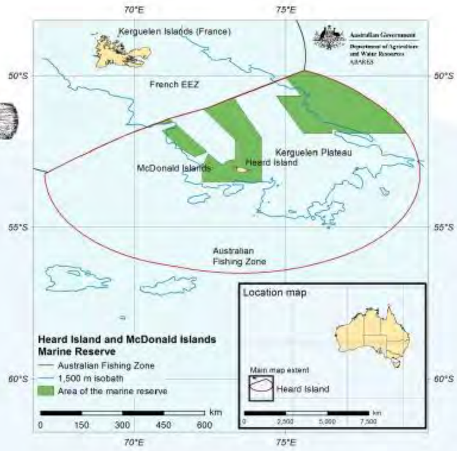
- WA Pilbara Fish Trawl (Interim) Managed Fishery
  - Catch ~2000 t, GVP ~\$5 million and ~6 licences
  - Demersal trawl targets:
    - Various tropical snappers (red emperor, rankin cod and bluespotted emperor)
  - Trawl bycatch / selectivity:
    - Dolphin BRD



Fish drawings: FAO and Rosalind Poole

Australian fish-trawl fisheries

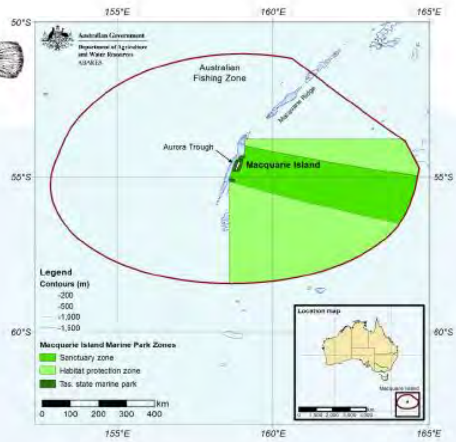
- Heard and McDonald Islands Fishery
  - Demersal trawl targets:
    - mackerel icefish; and
    - Patagonian toothfish
  - Mainly demersal longline now
  - Trawl bycatch / selectivity:
    - mesh size ≥ 120 mm for toothfish;
    - mesh size ≥ 90 mm for icefish; but
    - no relevant research.



Fish drawings: FAO and Rosalind Poole

Australian fish-trawl fisheries

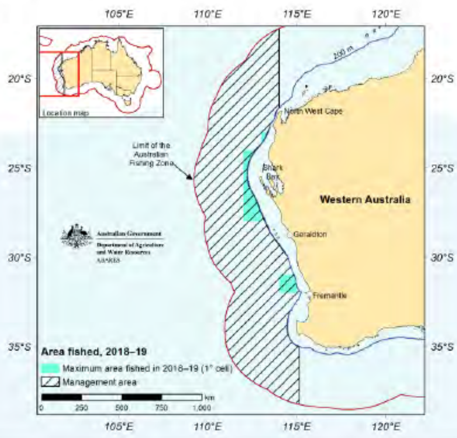
- Macquarie Island Fishery
  - Demersal trawl targets:
    - mackerel icefish; and
    - Patagonian toothfish
  - Mainly demersal longline now
  - Trawl bycatch / selectivity:
    - mesh size ≥120 mm for toothfish;
    - bobbin ≥520 mm;
    - rockhopper disc ≥520 mm; but
    - no relevant research.



Fish drawings: FAO and Rosalind Poole

Australian fish-trawl fisheries

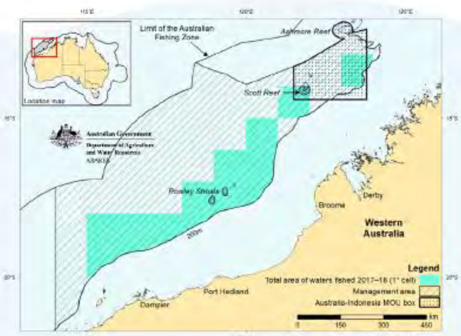
- Western Deepwater Trawl Fishery
  - Catch 100 t, GVP $confidential, and 11 permits,
  - Demersal trawl targeting:
    - ruby snapper;
    - deepwater bugs;
    - orange roughy, and oreos
    - now very low levels of fishing
  - Bycatch / selectivity:
    - codend mesh >50 mm; but
    - no relevant research available.



Fish drawings: FAO and Rosalind Poole

Australian fish-trawl fisheries

- North West Slope Trawl Fishery
  - Catch 80t, GVP $NA and 11 permits
  - Demersal trawl targeting:
    - snappers (historically); but
    - now mainly scampi.
  - Bycatch / selectivity:
    - codend mesh >50 mm; but
    - no relevant research available.



Fish drawings: FAO and Rosalind Poole

Australian fish-trawl fisheries

- Southern and Eastern Scalefish and Shark Fishery (SESSF)
  - Commonwealth Trawl Sector – GVP ~$ 50 m
    - Danish seine (20 vessels)
    - Otter trawl (32 vessels)
      - Demersal
      - Midwater (grenadier)
  - Great Australian Bight Trawl Sector
  - East Coast Deepwater Fishery
  - Trawl bycatch / selectivity:
    - Significant controls and research

Fish drawings: FAO and Rosalind Poole

Australian fish-trawl fisheries

SESSF gear restrictions

- Mid-water trawl:
  - All net mesh ≥90 mm
- Danish seine:
  - Codend ≥38 mm targeting school whiting
  - Codend ≥75 mm targeting tiger flathead
- Pair trawling:
  - All net mesh ≥90 mm

T0: Diamond mesh

Australian fish-trawl fisheries

SESSF CTS gear restrictions

- Demersal Otter Trawl (scalefish) mesh size:
  - wings and net mouth (shoulders, belly and veranda) ≥ 115 mm
  - codends comprising:
  - ≥ 90-mm single twine mesh; or
  - ≥ 102-mm double twine; or
  - ≥ 90-mm double-twine mesh with one or more BRD
    - a single ***square mesh*** (≥ 90 mm) panel in upper side of codend bag (minimum 15 bars X 20 bars); or
    - a single ***rotated (T90)*** mesh (≥90 mm) panel in upper side of codend bag (minimum 15 meshes X 18 meshes).


T0: Diamond mesh


T45: Square mesh


T90

Australian fish-trawl fisheries

SESSF GABTS gear restrictions

- Demersal Otter Trawl mesh size:
  - ≥90-mm single twine mesh mandated;
  - fishers typically use ≥ 100-mm mesh; and
  - code of conduct requires T-90 extension (94 mm)


T0: Diamond mesh


T90

Summary

- Key bycatch issues:
  - birds (CTS) interactions appear mostly resolved;
  - shark interactions in some areas are a concern;
  - seals are an ongoing issue (CTS);
  - rare catches of dolphins (CTS);
  - skates and rays (CTS and GABTS);
  - gulper shark exclusion in (CTS Royal Red Prawn Fishery);
  - general reduction of small fish bycatch; and
  - benthic impacts (although footprint has reduced)

Summary

- Research to date
  - CTS modifications:
    - larger diamond mesh in trawl body and codends;
    - square-mesh panels in codends;
    - shortened codends (to reduce seal catches – but didn't work); and
    - seal-excluder devices.
  - High-lift balloon trawl
  - GABTS:
    - T90 codends and extensions

Appendix 15. Industry presentation of international work to improve fish-trawl selectivity

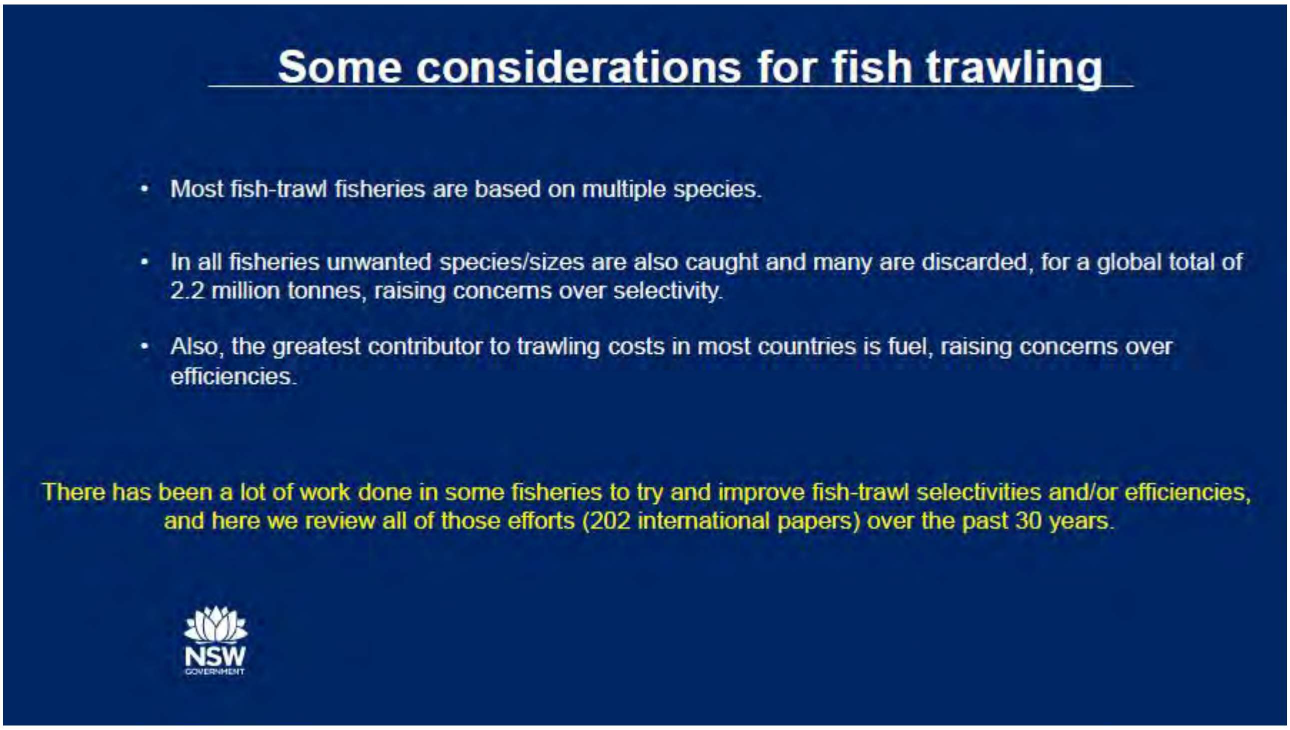
International efforts at improving fish-trawl selectivities/efficiencies

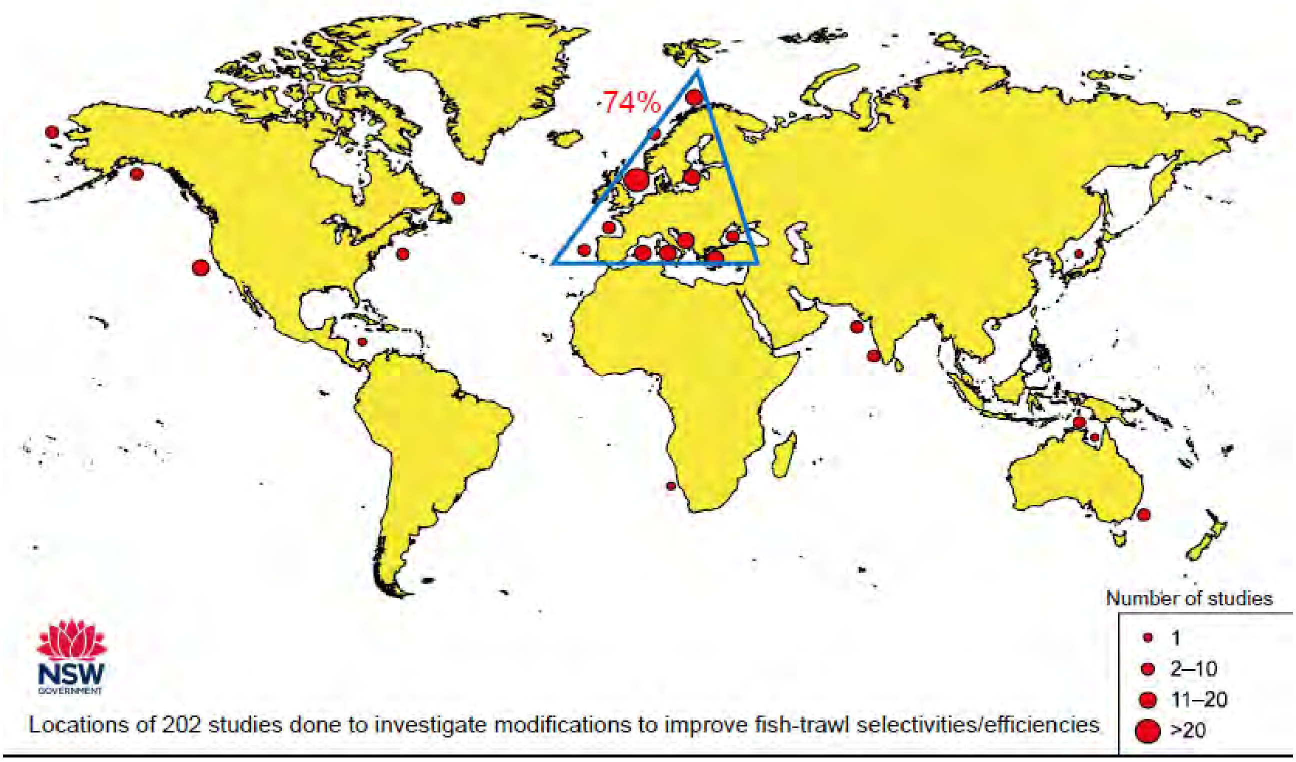
FRDC project 2019-27: 'Improving and promoting fish-trawl selectivity in the Commonwealth Trawl Sector (CTS) and Great Australian Bight Trawl Sector (GABTS) of the Southern and Eastern Shark and Scalefish Fishery (SESSF)'

Matt Broadhurst and Steve Kennelly
November 2020

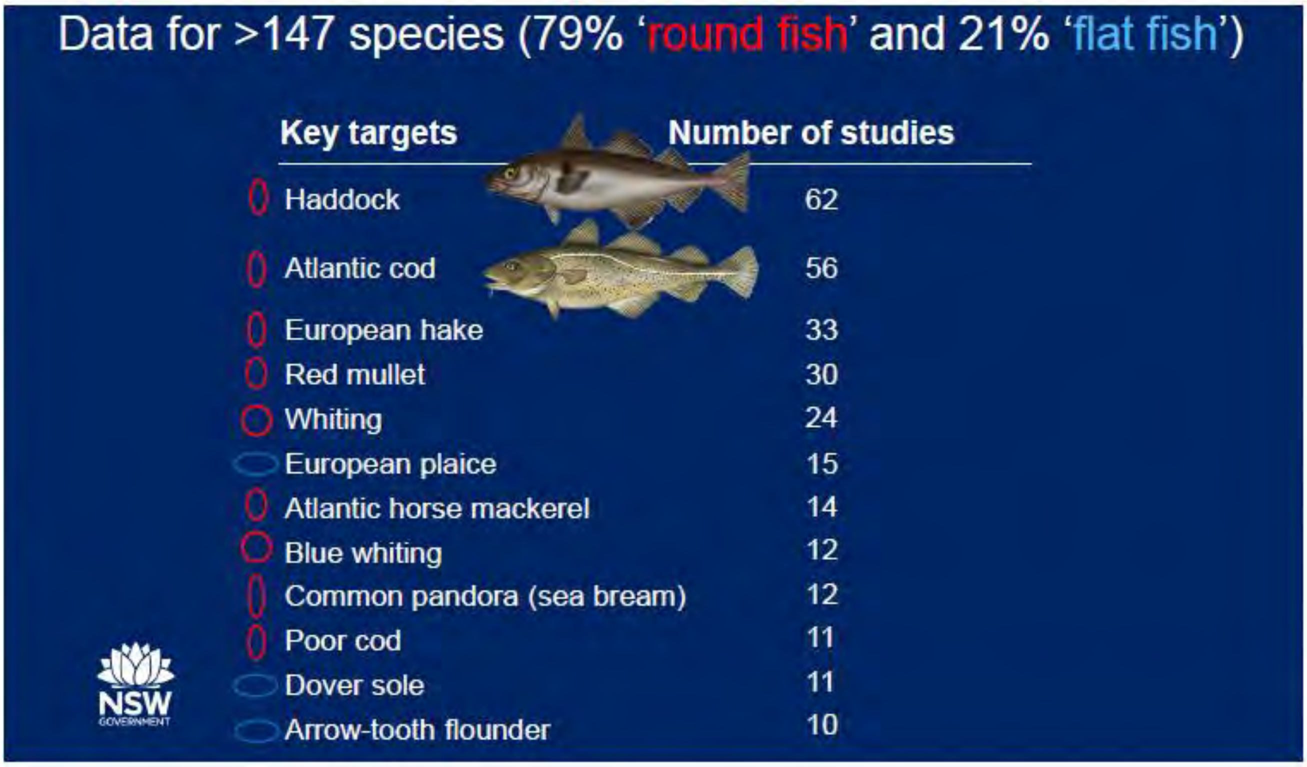
Bottom fish trawling around the planet

- Bottom fish trawling first started with the '*wondyrchoun*" (early form of beam trawl) in the 14th century.
- Beam trawling evolved into otter trawling (with two doors instead of a beam) in the mid 1800s.
- Currently, bottom otter trawling for fish occurs off >40 countries; from the tropics to the polar regions and at depths <20 to >2000 m.
- These fisheries produce almost 20 million t of fish each year (1/4 of the world's total marine production), made up of >300 key species.





Locations of 202 studies done to investigate modifications to improve fish-trawl selectivities/efficiencies



Data for >147 species (79% 'round fish' and 21% 'flat fish')
Key targets
Number of studies
Haddock 62
Atlantic cod 56
European hake 33
Red mullet 30
Whiting 24
European plaice 15
Atlantic horse mackerel 14
Blue whiting 12
Common pandora (sea bream) 12
Poor cod 11
Dover sole 11
Arrow-tooth flounder 10
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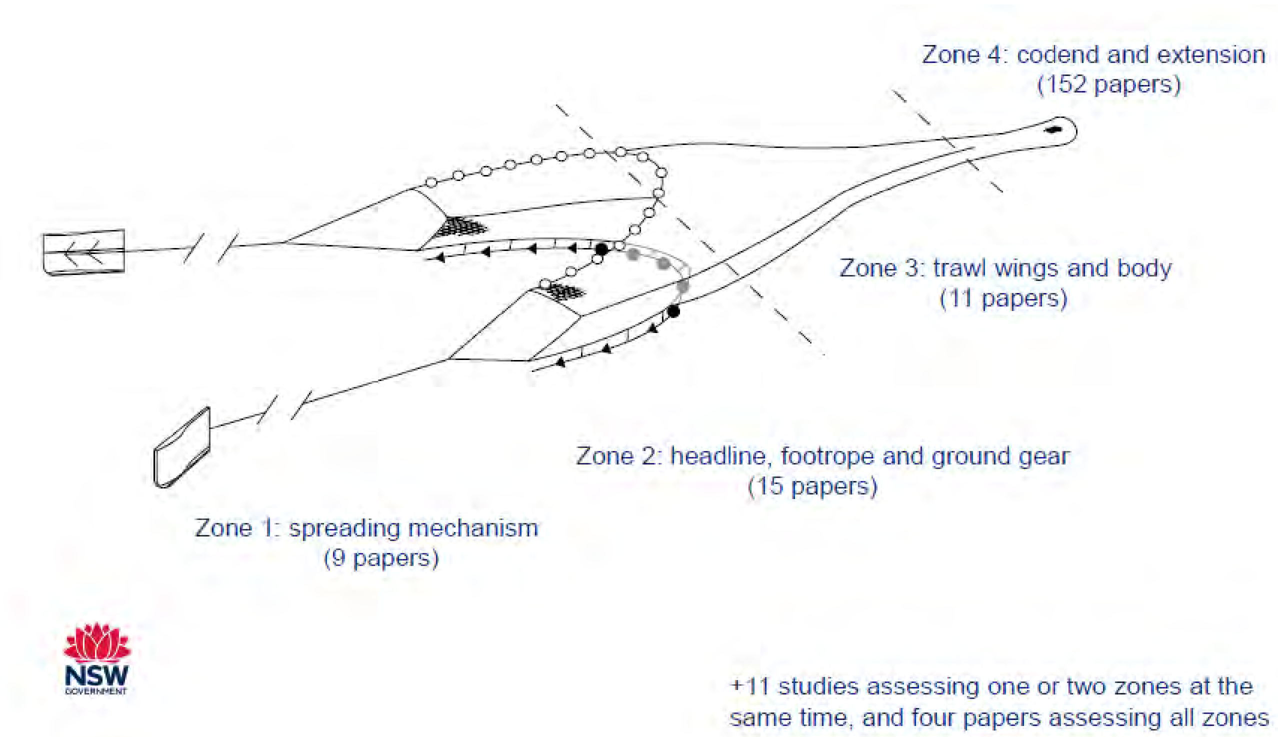
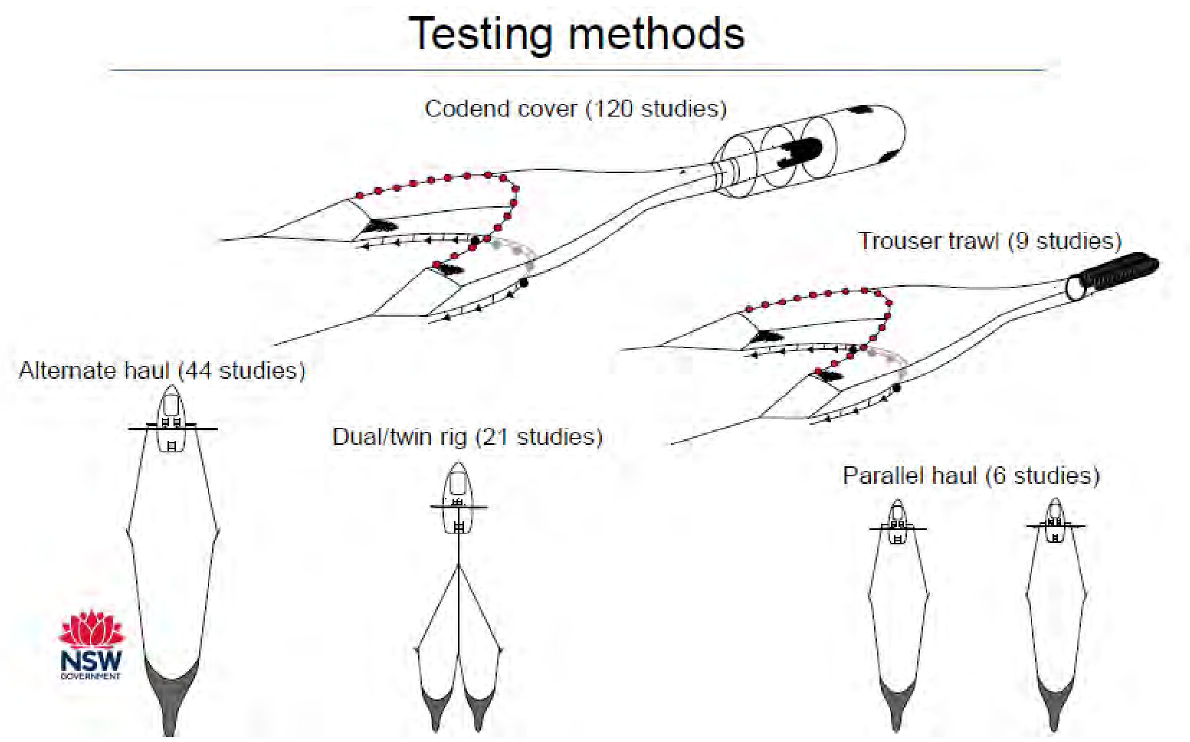


Zone 4: codend and extension
(152 papers)
Zone 3: trawl wings and body
(11 papers)
Zone 2: headline, footrope and ground gear
(15 papers)
Zone 1: spreading mechanism
(9 papers)
NSW GOVERNMENT
+11 studies assessing one or two zones at the same time, and four papers assessing all zones


Testing methods
Codend cover (120 studies)
Trouser trawl (9 studies)
Alternate haul (44 studies)
Dual/twin rig (21 studies)
Parallel haul (6 studies)
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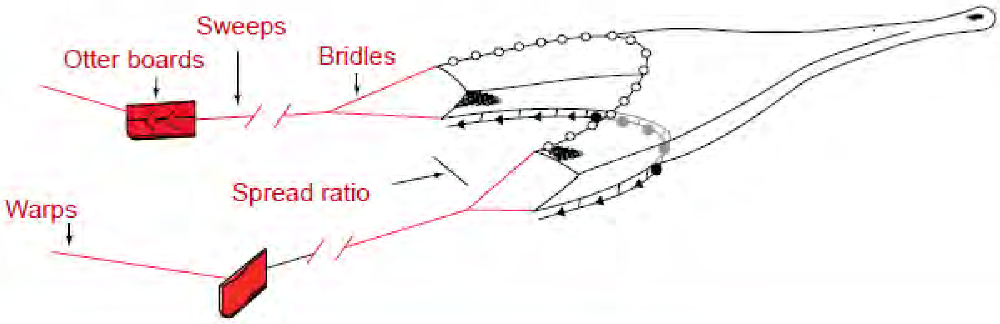
GOVERNMENT


Testing methods
Load cells
Trawl monitors
Cameras
NSW
GOVERNMENT

Zone 1 modifications

Nine papers

- Raising sweeps higher off the bottom (in relevant fisheries);
- Changing warp, sweep or bridle lengths and angles; and
- Optimising spread ratio for particular trawl designs.



Zone 1 modifications: results

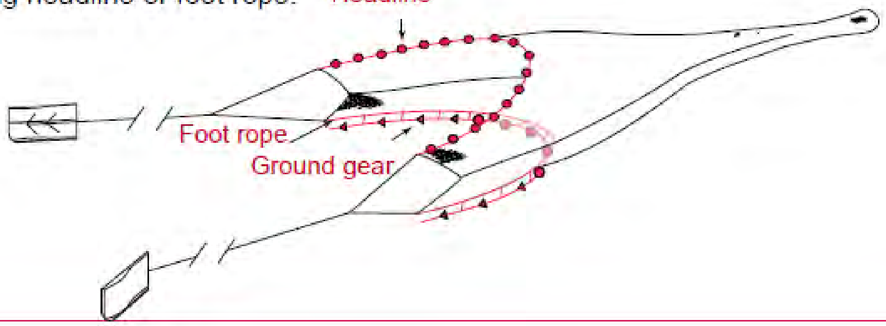
Modifications	Effects
Raising sweeps off the bottom	Reduced flat fish catches (during daylight) without affecting targeted round fish.
Changing warp, sweep or bridle lengths and angles	As might be expected, longer warps, sweeps and bridles generally caught more of most round fish, but catches of some small fish decreased with longer sweeps.
Variable spread ratios	Spread ratio needs to be optimised for trawl design. One study showed an increase in catches of round fish at lower spread ratios (as headline height increased).

All with potential for reducing drag, so +effects on fuel.....

Zone 2 modifications

15 papers

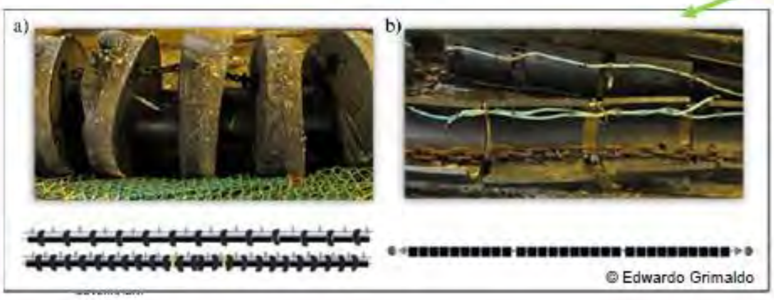
- Long cutaway headropes ('topless trawl');
- Lowered headlines;
- Raised foot ropes (using floats, spokes, or rubber discs);
- Alternative ground gear ('semicircular spreading ground gear' or SCSG), rollers or larger discs;
- Tickler chains; and
- Lights along headline or foot rope.



Zone 2 modifications: results

- Topless trawl and other cutaway head rope designs reduced catches of some round fish, including bottom-dwelling fish, but maintained catches of flat fish.*

*Good potential for reducing drag, so +effects on fuel…..

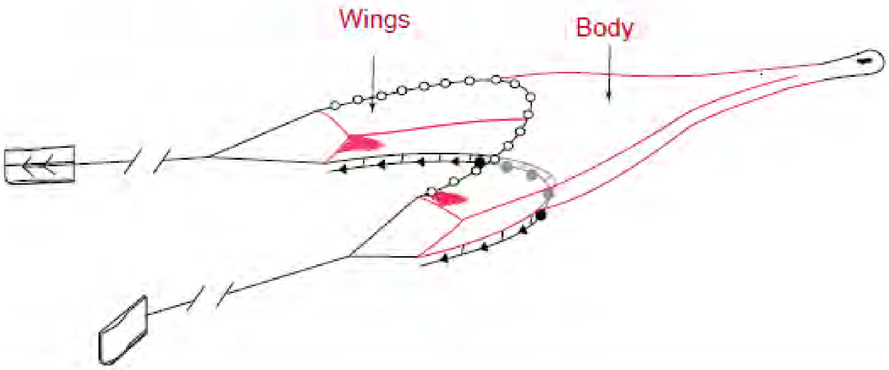


- SCSG reduced loss of fish under foot rope and caught more larger fish.
- Larger discs had variable effects on catches (increased flatfish and reduced cod catches and benthic disturbances).

Zone 3 modifications

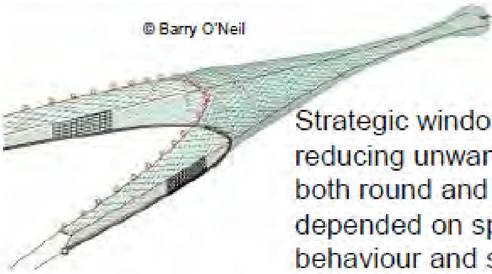
11 papers

- Larger diamond mesh throughout;
- Horizontal separator panels; and
- Strategic 'windows', usually diamond-shaped mesh.

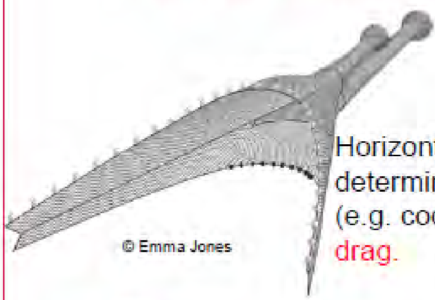


Zone 3 modifications: results

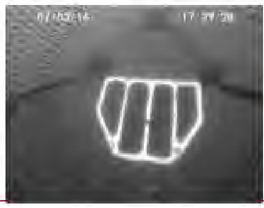
Larger diamond mesh useful for reducing catches of round fish, depending on target sizes. And with good potential for reducing drag, so +effects on fuel.



Strategic windows useful for reducing unwanted sizes of both round and flat fish, but depended on species behaviour and shape.



Horizontal separator panels are a simple technique for determining where different species orientate in a trawl (e.g. cod go up and haddock go down). But will increase drag.

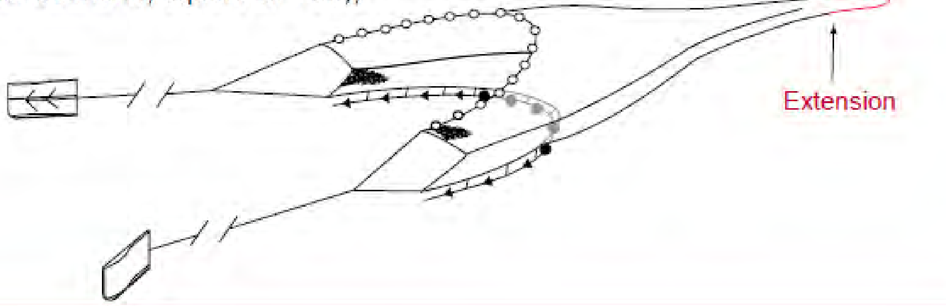


LEDs had highly variable effects, but were effective at directing some fish to windows (at night).

Zone 4 modifications

152 papers

- Larger diamond mesh throughout;
- Reduced codend circumference;
- Thinner, more flexible twine;
- Remove or change strengthening bags, chafing gear or lastridge ropes;
- Square- or T90 mesh codends;
- 'Windows' (larger diamond, square or T90);
- Devices to direct catches to larger mesh openings;
- Grids for sorting sizes;
- Grids for sorting species; and
- Grids AND windows.



Zone 4 modifications: results

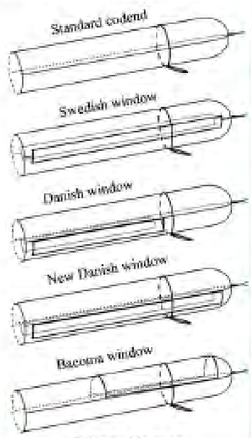
No effects on drag and therefore fuel

Optimising diamond mesh openings for sizes of target species always reduced unwanted catches.

Reducing twine diameter and codend circumference has also helped to improve selectivity in many fisheries.

Replacing diamond mesh with square mesh or T90 throughout can be effective for reducing unwanted round fish catches, but there are issues with strength for square mesh.

Issues have been mitigated by just using strategic windows, which mostly work better the closer they are to the end of the codend.



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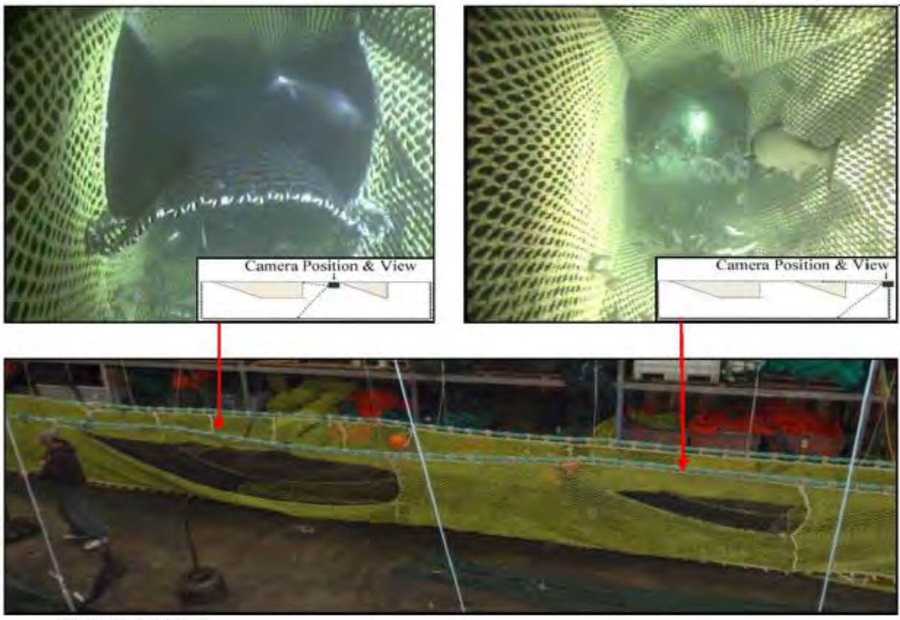
Zone 4 modifications: results



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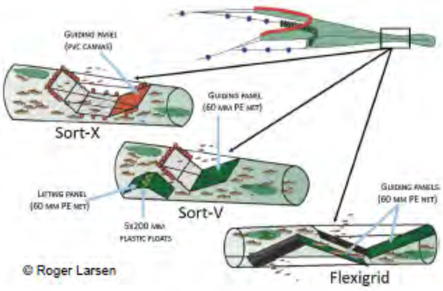
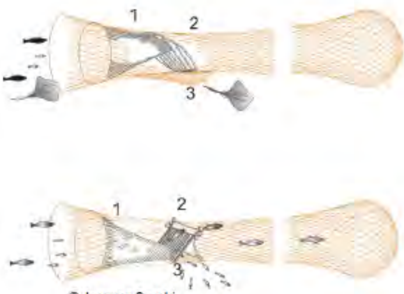
Sometimes escape windows work better with guiding panels (but they can get complex).

Zone 4 modifications: results



© Roger Larsen

Grids for sorting sizes have worked well in fisheries where there are only one or two key targets (e.g. cod and/or haddock), and have considerably reduced catches of small fish close to legal size without too many impacts on legal sizes. There have been some issues with handling, and the flex-grid is now preferred in legislated fisheries (Norwegian Sea).



© Jacques Sacchi

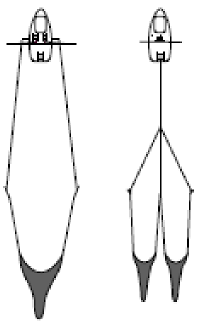
Grids for sorting species are usually restricted to those fisheries where there is an issue with threatened animals (e.g. turtles), but can be 100% effective with minimal loss of the targeted species (both round and flat fish).

Combinations of all zones

four papers

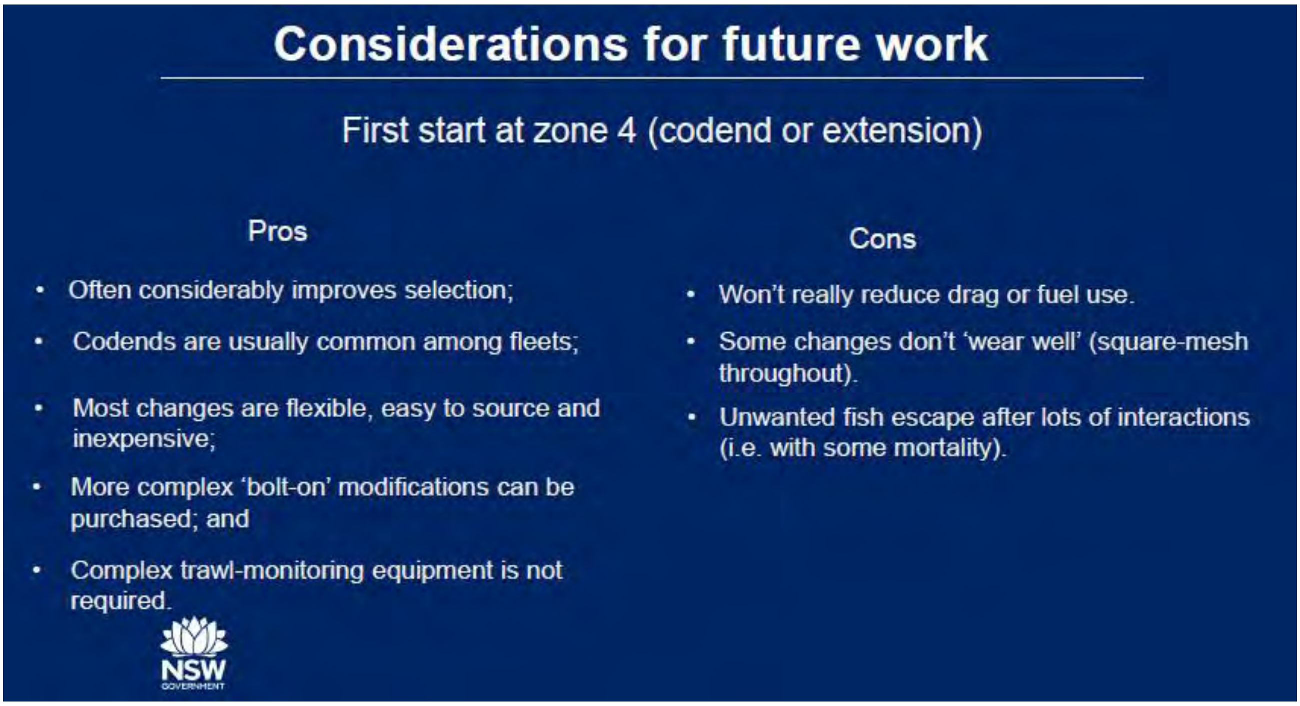
- Entirely new trawl designs for a particular fishery (including codend mesh size/shape; and
- Single vs dual rig.

Combinations of zones results



In most cases, it is difficult to determine the key effects of modifications to all zones, because these are a 'packet of changes'.

One study assessed single vs dual rig (targeting haddock, cod, European plaice, lemon sole, angler fish and Norway lobster) and showed improved catches of flatfish in the dual rig. There is also good potential for reducing drag and so +effects on fuel with dual rig.


Considerations for future work
First start at zone 4 (codend or extension)
Pros
Often considerably improves selection;
Codends are usually common among fleets;
Most changes are flexible, easy to source and inexpensive;
More complex 'bolt-on' modifications can be purchased; and
Complex trawl-monitoring equipment is not required.
Cons
Won't really reduce drag or fuel use.
Some changes don't 'wear well' (square-mesh throughout).
Unwanted fish escape after lots of interactions (i.e. with some mortality).
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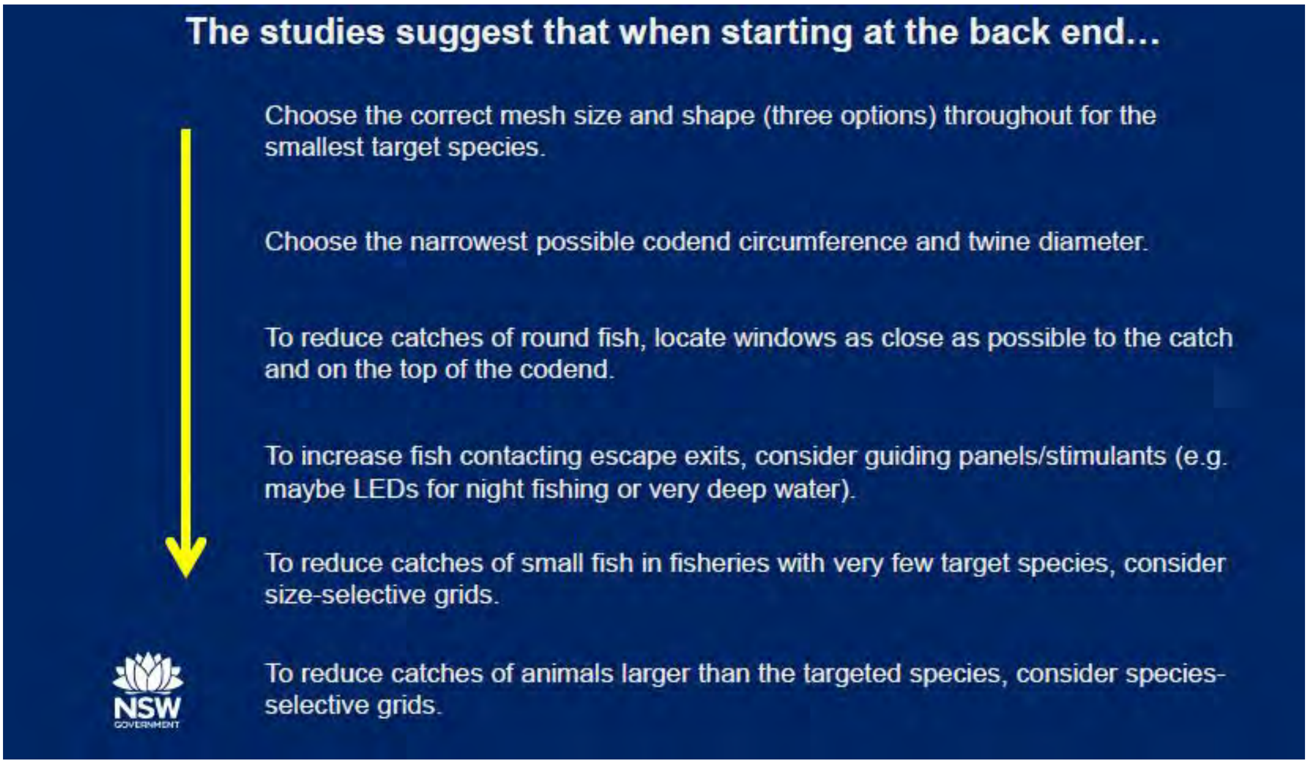
The studies suggest that when starting at the back end…
Choose the correct mesh size and shape (three options) throughout for the smallest target species.
Choose the narrowest possible codend circumference and twine diameter.
To reduce catches of round fish, locate windows as close as possible to the catch and on the top of the codend.
To increase fish contacting escape exits, consider guiding panels/stimulants (e.g. maybe LEDs for night fishing or very deep water).
To reduce catches of small fish in fisheries with very few target species, consider size-selective grids.
To reduce catches of animals larger than the targeted species, consider species-selective grids.
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Considerations for future work

After optimal codends/extensions are determined, assess the front end (zones 1 to 3)

Pros

- Often considerably improve selection;
- Can reduce drag and fuel (especially zone 3 refinements because they affect twine area);
- Most changes are flexible, easy to source and inexpensive;
- Can purchase some bolt-on modifications (e.g. LEDs); and
- Unwanted fish often avoid the trawl entirely with maximum survival.

Cons

- The front ends of trawls are often not exactly the same among fleets;
- Can be difficult to determine key factors improving selectivity/efficiency; and
- Need trawl-monitoring equipment to assess.

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At the front end…

Choose the largest possible diamond mesh sizes throughout.

Choose the narrowest possible twine diameter.

Install a horizontal separator panel(s) to confirm species-specific behaviour (for the future refinement of modifications).

Depending on species distributions, assess windows with different mesh shapes (e.g. T90) in the wings, or top panels.

To increase fish contact with panels/windows, consider guiding panels/stimulants (e.g. LEDs).

Depending on species distributions, assess refined ground gears.

Optimise bridle and sweep lengths for target species.

Optimise spread ratio.

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Conclusions

- Lots of studies done, but most in Europe (74%), with only a handful of species and especially haddock and cod.

- Lots of repetition in only a few fisheries, and if the same effort applied to cod and haddock is extended to the other 200-300 species around the planet, we will need thousands of studies.

- No fishery has solved all of the issues surrounding selectivity.

- While some work will always be ongoing, to maximise benefits for industry, it is imperative that modifications are tested across the full range of conditions, and that fishers are involved in all aspects of fishing-gear evolution and testing.

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Appendix 16. Broadhurst, M., Kennelly, S. and Knuckey, I. 2021. Trawling international research for better fishing practices. FISH, March 2021, 1p.

MORE INFORMATION
Matt Broadhurst, matt.broadhurst@dpi.nsw.gov.au
FRDC RESEARCH CODE: 2019-027

Trawling international research for better fishing practices

Excess fuel use and unwanted bycatch are ongoing challenges for trawl fishing in Australia and around the world

By **Matt Broadhurst, Steve Kennelly** and **Ian Knuckey**

Around the world, research teams, including fishers, scientists and managers, have strived to improve the process of trawling for fish to reduce unwanted catches and improve fuel efficiency by reducing drag from nets.

A recently completed systematic review of more than 200 scientific reports, encompassing about 40 fisheries and 147 species, has identified lessons Australian fisheries can take advantage of and identified gaps that future local research can help to address.

It is part of a larger project that aims to improve and promote fish-trawl selectivity and efficiency in two important Australian fish-trawl fisheries: the Commonwealth Trawl Sector (CTS) and the Great Australian Bight Trawl Sector (GABTS) of the Southern and Eastern Scalefish and Shark Fishery (SESSF).

The review marks the completion of phase one of the project, which is funded by the FRDC and NSW Department of Primary Industries (DPI). Phase two will involve working with local industry participants to identify research priorities.

Key findings

The international review describes numerous technical modifications to fish trawls and the positive and negative aspects of their testing and adoption.

- Much of the research (nearly 75 per cent) has been restricted to European fisheries and especially those targeting cod and haddock, and this has strongly influenced the choice of modifications tested elsewhere.
- Most efforts have focused on the back end of trawls, by increasing or varying mesh openings in codends to match the sizes of unwanted catches via larger, diamond-shaped mesh, or turning meshes 45 degrees or 90 degrees, either throughout or as strategically placed windows. In some fisheries, different grids have also been shown to work well at either excluding some undersize fish or large unwanted animals (for example, sharks and rays).
- Relatively few studies have modified the front sections of trawls. Some changes to panels and rigging have realised selectivity benefits depending on the species, and this area has the greatest potential for reducing drag and, therefore, fuel and operating costs.
- The successful adoption of modifications has required very close industry consultation throughout all stages of development.

The review also found a large amount of repetition between studies, attributed in part to problems with scientific replication and uncontrolled or confounded factors in experimental designs. This suggests rigorous, standardised, scientific assessments combined with close stakeholder liaison are almost as important as the modifications being tested.

Specific modifications for fish trawls used in the CTS and GABTS will be identified and progressed through industry consultation.

The review identifies a framework for resolving key issues in the research and testing process, depending on the options tested or available in a particular fishery, which allows for modifications to address the unique biological, environmental and technical factors of specific fisheries.

A 'toolbox', or suite of possible modifications, that might be applied depending on specific issues in a fishery has been developed from the review.

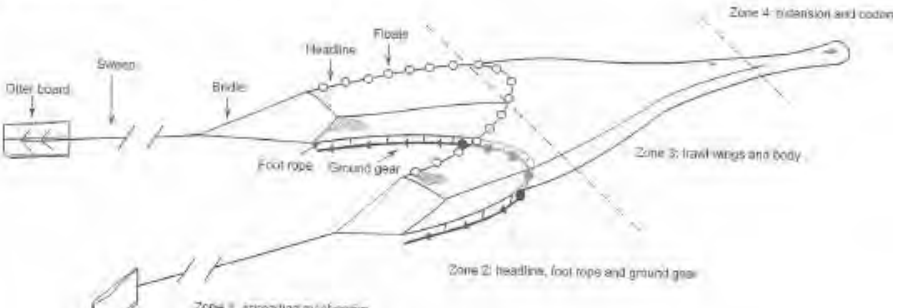
Available modifications can be assessed with a focus on either simple or more complex options. Simply reconfiguring codend mesh could improve trawl selectivity. A more complex modification might involve changing the front end of the trawls to improve overall efficiencies.

The results of the review have been presented to fishers through the South East Trawl Fishing Industry Association and the Great Australian Bight Industry Association. The review has also been submitted to an international scientific journal for publication.

During the next phase of the project, the research team will work with SESSF trawl fishers to further investigate and support the widescale voluntary adoption of appropriate best practice technologies to reduce bycatch and improve efficiency in Australia's fish-trawl fisheries. F

Specific modifications for fish trawls used in the CTS and GABTS will be identified and progressed through industry consultation.

BASIC TRAWL NET DESIGN



SOURCE: NSW Department of Primary Industries

Appendix 17. Summaries of project work communicated via email and/or social media to CTS and GABTS fishers

Questions for selected fishers during phase 1

Background

In response to a COMRAC research priority in November 2018, a new project funded by NSW DPI and FRDC is about to start. The project title is: "**Improving and promoting fish-trawl selectivity in the Commonwealth Trawl Sector (CTS) and Great Australian Bight Trawl Sector (GABTS)** of the Southern and Eastern Shark and Scalefish Fishery (SESSF)**"**

Reducing bycatch benefits the commercial fishing industry in several ways, but primarily it helps achieve optimal efficiency while improving sustainability and public perception; all of which ultimately increase fishing viability into the future.

Like in all fisheries, trawlers targeting fish in Australia catch some unwanted species and/or sizes of targets, which are then discarded. Some previous work with fish trawlers, and especially those off southern NSW, has shown that simple gear modifications can reduce the amount of small fish and other unwanted species caught by up to 60%. As a result of this early work, there has been wide-scale adoption of various gear modifications/refinements by industry, and subsequent legislative changes were implemented by early 2006.

More recent industry-led changes to mesh sizes and orientations, and the use of hydroacoustic gear monitoring equipment are currently being employed by some operators in the CTS (and GABTS) and are reportedly helping to reduce bycatches, but still maintain target catches. Formally assessing the performance of these modifications catches is a high priority because it could help to encourage uptake among other Australian fish-trawl operators.

Considering the above, the aim of this research project is to work with trawl fishers to prioritise, assess and then refine modifications designed to minimise unwanted bycatches while maintaining target catches. It is hoped the project will support the wide-scale voluntary adoption and ongoing exploration of appropriate best-practice technologies.

The project team comprises researchers (Matt Broadhurst and Ian Knuckey), managers (Dan Corrie) and Executive Officers from the two key industry bodies (SETIA and GABIA) and will run for four years from August 2020 across three phases. The first phase (over six months) is to complete reviews of what has already been achieved in the fisheries and what might be achievable (looking at work done overseas). And then, with support from industry, the next two phases (each 21 months) will involve obtaining data on the effectiveness of priority modifications throughout the fisheries (on chartered vessels).

For any information on the project, please contact Matt Broadhurst (matt.broadhurst@dpi.nsw.gov.au)

The following anonymous questions will help to complete the first phase of the project.

Date: _______________

Which fishery? CTS or GABIA (circle one)

What are your common grounds worked and depth? ____

What are your key target species and sizes:____

____
____
____
____
____
____
____

What do you consider are the problematic bycatch species and sizes?_________________________

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Have you tried any modifications to reduce bycatch, and if so any success?___________________

____
____
____
____

Any concerns or suggestions for the project?____

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Effects of ground-gear bobbin diameter on the performance of a trawl in the Commonwealth Trawl Sector (CTS)

Recently, using funding from the Fisheries Research and Development Corporation and NSW Department of Primary Industries, a four-year project was started that involves working with CTS and Great Australian Bight Trawl Sector (GABT) fishers to prioritise, assess and then refine modifications designed to minimise unwanted catches and improve trawl efficiencies. It is hoped the project will support the wide-scale voluntary adoption and ongoing exploration of appropriate best-practice technologies.

The first experiment that was suggested, and has now been completed, involved investigating the relative catching and engineering performances of different-sized discs in bobbin gear. According to a recent industry review, nearly 90% of CTS and GABT fishers use a maximum bobbin disc diameter of 6–10 inches.

The work was done off Ulladulla during 12 fishing days in May and April, 2021 and using a Hampidjan 'H-Top' trawl with 39 m long ground gear. The ground gear was separated into two wing sections (each 13 m and with maximum disc sizes of ~4 inch) and a removable centre section (13 m). Three centre sections were constructed; all identical with the same diameter spacers (~2.3 inch or 60 mm), but different maximum disc diameters: 4, 7 or 10 inches (Figs 1 and 2). The centre sections were designed to be attached and removed to the trawl at sea using D-links (which took ~15 min).

Figure 1. Three centre sections of ground gear that were tested.

The towing order of the trawl with the different centre ground gears was altered each day, and 12 tows (~2.5 h each) of each configuration were completed (i.e. 36 tows in total). Half the tows were done in deep water (480–580 m) and the rest in shallow (110–200 m). Data were recorded for otter-board spreads and headline heights and the numbers, weights and sizes of key species.

In total, the retained and discarded catches were 12.8 and 9.8 t, respectively. Key retained catches were bigeye ocean perch (~2.9 t) and pink ling (~1.9 t) in deep water and ocean leather jacket (~2.9 t) and tiger flathead (~1.1 t) inshore. The main discarded catches were smooth and falseband whiptails (0.9 t).

Changing the centre ground gear had no effects on otter-board spread (average of ~153 m across all tows) or headline height (~3.8 m across all tows), but fishing depth and towing speed did affect trawl changes. Regardless of the ground gear, there was an average 13 m increase in otter-board spread and a 33 cm reduction in headline height for every 100 m of additional depth. Also, otter-board spread increased by 3.6 m for every 0.2 kn increase in speed across the ground (towing speeds were 2.3 to 3.5 kn).

In terms of catches, the different ground gears did not significantly affect the total retained or discarded amounts or the numbers, weights or sizes of the individual species listed above. Mean catches in the trawl were quite similar (and consistent for the total categories) among tows for most species. The only species to show marginal consistent changes in mean catches were bigeye ocean perch and whiptails, with slightly lower amounts in the trawl when rigged with either the 7- or 10-inch discs than the 4-inch discs. But these differences were not statistically significant.

Future work is now being planned to assess other prioritized changes to trawls used in the CTS and also GABTS. For further information contact Matt Broadhurst on 02 6656 8905.

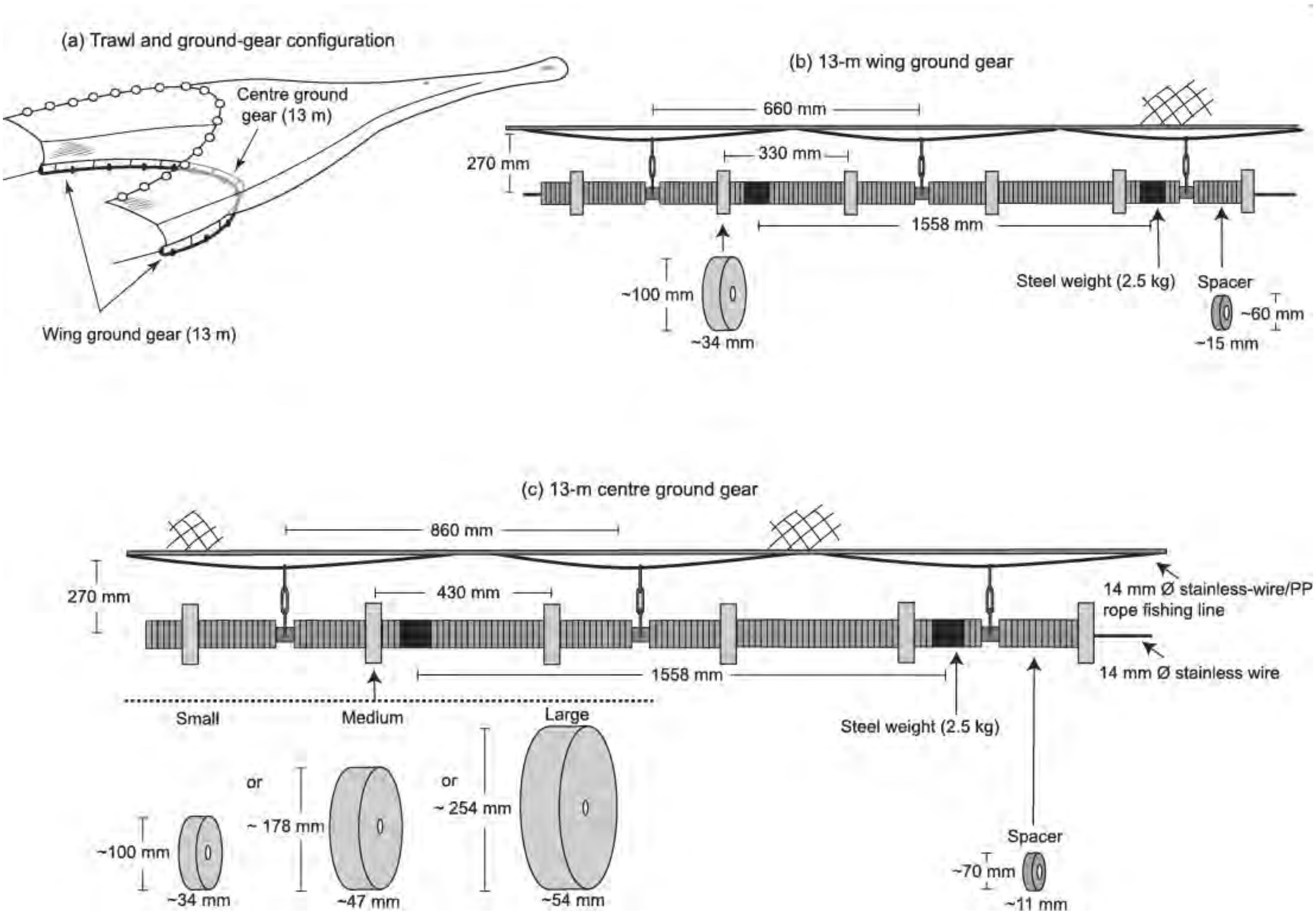

Figure 2. Diagrams of the (a) trawl and ground-gear configuration with (b) 13-m wing sections, and (c) centre section. Ø, diameter; PP, polypropylene

Summary on SETFIA Facebook page, 8 October 2021

The FRDC has funded a project to improve trawl efficiency and selectivity in SE Australia. The project is being administered by NSW DPI, and builds on previous work done in several regional fisheries. The first experiment in the project investigated the effects of 4-, 7- and 10-inch bobbins on the performance of a trawl fished inshore and offshore from Ulladulla. The different bobbin sizes did not statistically affect the retained or discarded catches, and they didn't really change the footprint of the gear (and certainly not the spread) on the seabed. The data imply minimal benefits in using different bobbin sizes (within the range tested) to try to select different fish species.

Instead, during the next experiment, the project will use horizontal separator panels throughout the trawl, and also just at the codend to see if desirable species (like flathead and ling) and others that should be avoided (like redfish and eastern gemfish) consistently orientate at different heights in the water column at the mouth of the trawl, and then once they enter the trawl. If there are consistent differences in vertical orientations, then there may be options to investigate modifications to the trawl body (and possibly also the codend) to reduce unwanted catches.

Interested fishers can contact Matt Broadhurst at NSW DPI on 0408 110 448 for more information. An EOI will soon be issued looking for suitable trawl vessels for the above work.

T90 mesh codend fished in the Great Australian Bight

- Like all fish trawls, those used in the Great Australian Bight are not selective for the targeted species, and so sometimes, unwanted catches (bycatch) are caught onboard and discarded dead.
- As part of a recent initiative to improve fish-trawl selectivity, an industry-developed modification involving orientating conventional meshes (94-mm mesh opening) 90 degrees in a codend (to increase openings) was compared against the traditional codend design (Figs 1 and 2).
- The modification did not reduce the bycatches of any species, but it did improve the quality of the key target (deepwater flathead), which was attributed to fewer debris (sand and particles) in the codend.
- The absence of any effects of the T90 mesh on species or size selection might reflect the small mesh size relative to most key species and the use of thick, double twine which probably negated some of the anticipated increases in mesh openings.
- Larger mesh sizes (~98–110 mm) orientated at 90 degrees either in the front section of the codend or throughout might maintain an improved catch quality while concomitantly reducing at least some unwanted bycatch, including small deepwater flathead (< 35 cm TL) and also other species, like latchets.

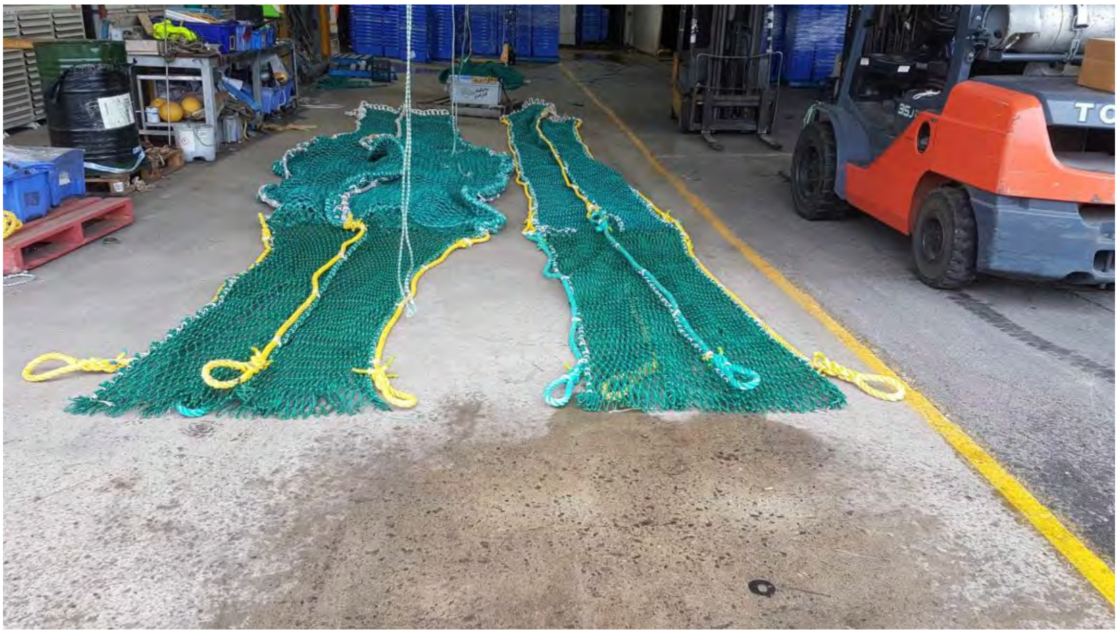

Fig. 1. Photograph of the T90 (left) and traditional (right) codends compared in the Great Australian Bight.

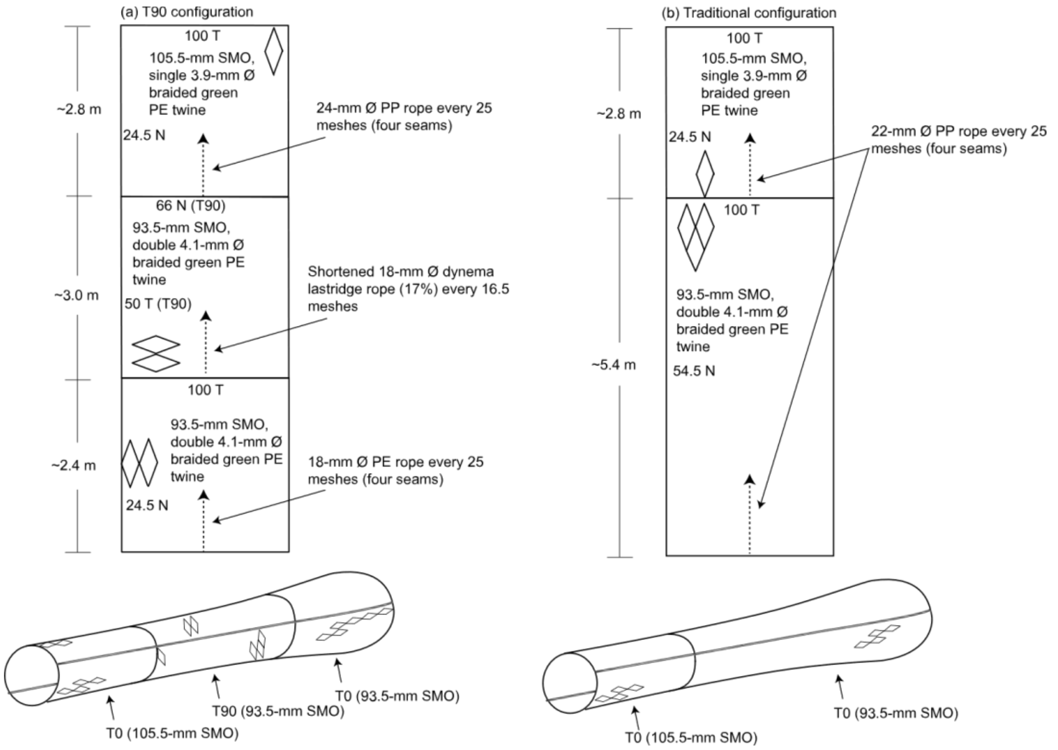

Fig. 2. Schematic diagrams of the (a) new T90 and (b) traditional codends compared in the Great Australian Bight.

Relative selectivity of larger T90 codend sections on a fish trawl in the Great Australian Bight

- Fish trawls catch unwanted species that are discarded, often dead, which represents a waste.
- As part of an initiative to improve Australian fish-trawl selectivity, an industry-developed modification involving orientating conventional meshes (94-mm mesh opening) 90 degrees in a codend ('T90' mesh) was compared to new designs comprising larger T90 mesh (105 mm).
- The larger-meshed T90 codends allowed many immature individuals (<40 cm total length) of the key target and quota species (deepwater flathead) to escape, and reduced catches of some discarded species.
- However, the larger-meshed T90 codends also lost some other retained, non-quota species.
- Slightly smaller T90 mesh sizes (~100 mm) might maintain catches of retained species, while still allowing juvenile deepwater flathead to escape.

Using a separator panel to determine fish movements during capture in a trawl

In 2020, using funding from the Fisheries Research and Development Corporation and NSW Department of Primary Industries, a four-year project was started that involves working with Commonwealth Trawl Sector (CTS) and Great Australian Bight Trawl Sector (GABTS) fishers to prioritise, assess and then refine modifications designed to reduce unwanted catches and improve trawl efficiencies. Some experiments have been completed, including assessing the effects of: (1) different bobbin disc sizes in the CTS; (2) a square-mesh panel to allow small eastern school whiting to escape inshore trawls; and (3) T90 mesh in the GABTS.

In multi-species fisheries such as the CTS and GABTS, ideally trawlers would maintain catches of important commercial species (like tiger flathead), while minimising unwanted catches (like skates and rays) or species classified as overfished or under rebuilding strategies (e.g. school shark, gemfish, redfish, trevally, and jackass morwong). To learn more about where these different species orientate in trawls (and possibly suggest new designs for testing), an experiment was done recently in the CTS using a horizontal-separator panel (HSP) throughout the aft body, leading to separated (dual) lengtheners and codends (Fig. 1). The lengtheners were attached to a wire-rope ring with a 2.5 m cross bar, which was secured to the aft trawl (Fig. 1). The aim was to fish the trawl with both the HSP and dual lengtheners/codends, and then just with the dual lengtheners/codends to determine if wanted and unwanted species orientate at different heights near the mid trawl, and then at the aft trawl near the lengthener (Fig. 1).

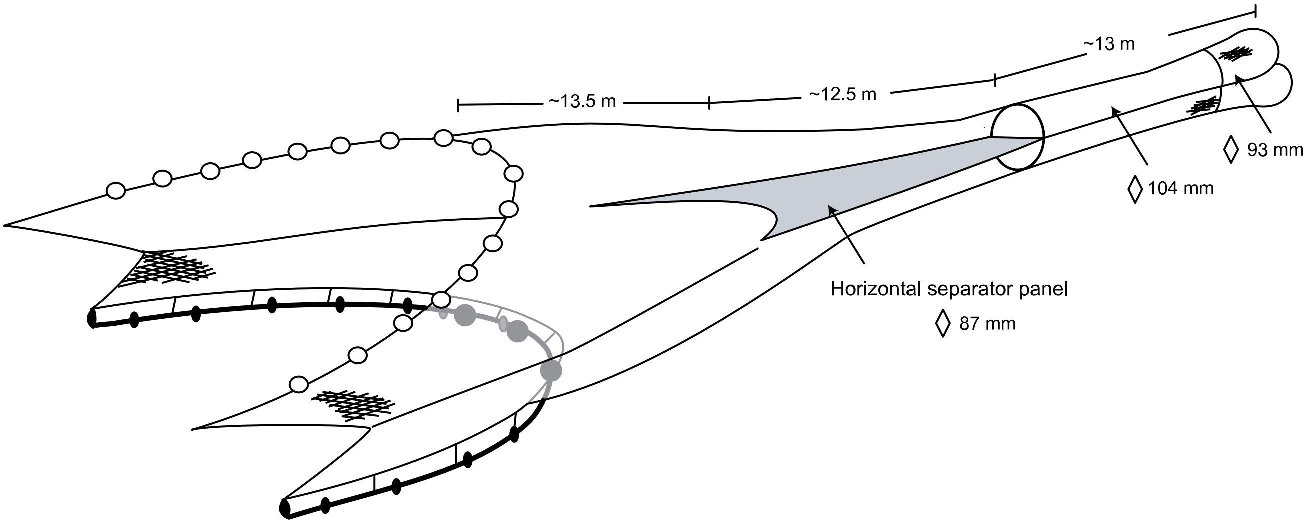

Figure 1. The trawl with the horizontal separator panel installed and dual (upper and lower) lengtheners and codends.

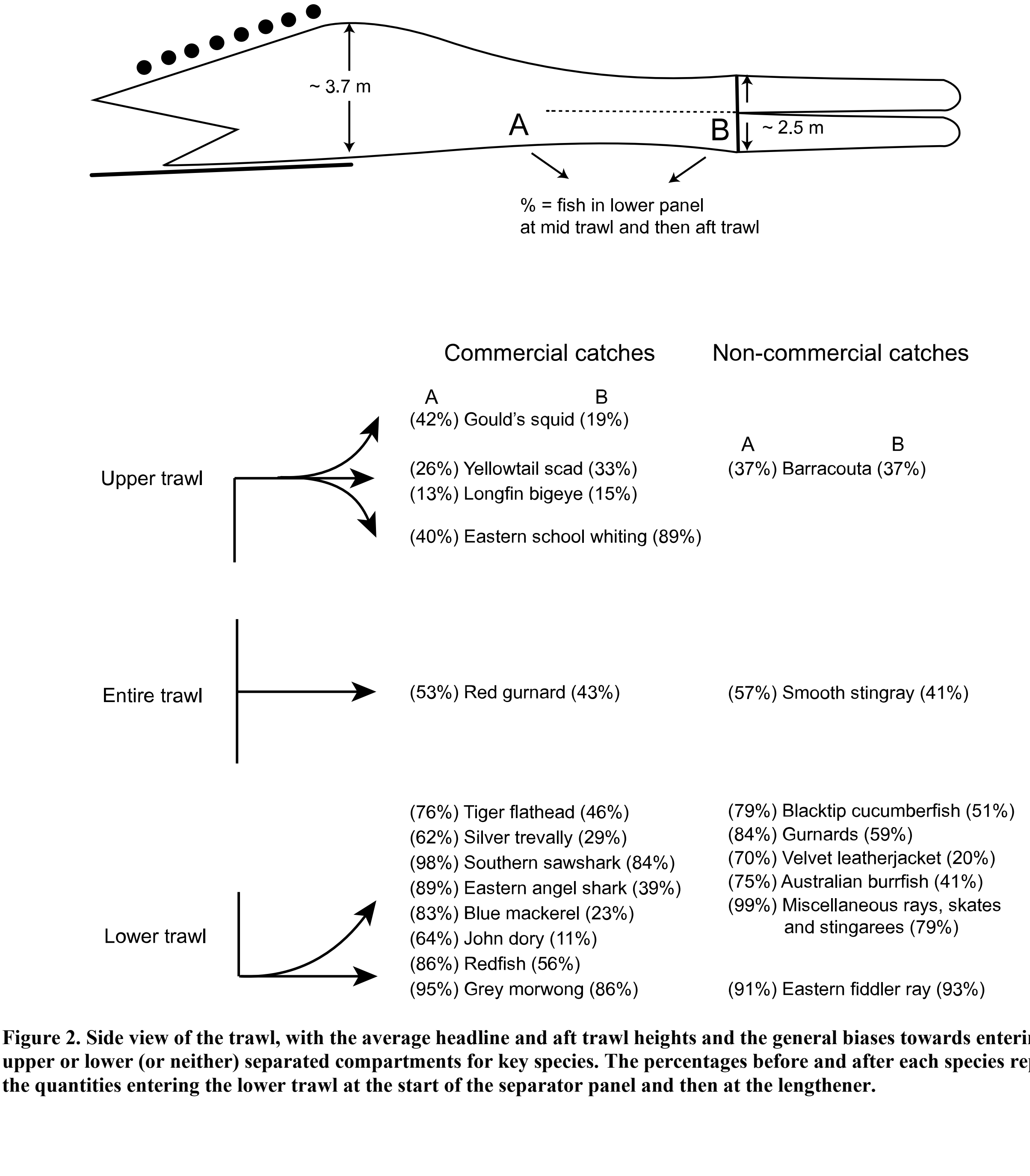

Figure 2. Side view of the trawl, with the average headline and aft trawl heights and the general biases towards entering the upper or lower (or neither) separated compartments for key species. The percentages before and after each species represent the quantities entering the lower trawl at the start of the separator panel and then at the lengthener.

The work was done off Ulladulla and Bermagui (53–420 m) during 10 days in April and May 2022 using a two-seam trawl with a 42 m headline. Seventeen hauls were done with the HSP installed, and then 15 hauls with just the dual codends.

The HSP did not affect the trawl opening, which maintained a fairly consistent height of ~3.7 m. In total, ~20 t was caught; of which 8 t comprised ~46 commercial species and 12 t included ~33 non-commercial species. The commercial species entered the aft trawl at varying heights, but many, including tiger flathead mostly entered low in the trawl (i.e. 76% of fish), and then rose up to present similar catches in each of the dual codends (Fig. 2). The only commercial species to move downwards at the aft trawl body was eastern school whiting and the only commercial species to consistently stay low was grey morwong (Fig. 2). Non-commercial catches were biased towards rays, skates and stingarees, and all except smooth stingrays mostly stayed low, with only some (proportionally fewer than the key commercial species) eventually rising upwards.

The data suggest that future modifications to fish trawls could be considered for regional testing, including lowering headlines and increasing mesh sizes in the upper forward trawl body to reduce drag (which might not greatly affect catches of commercial species) and/or changing the lower aft trawl body to separate unwanted rays and skates, possibly via larger meshes/drop-out panels or even bottom-opening grids at some places and times. Because of their behaviour, it might also be possible to similarly separate out some morwong.

Future work is now being planned to assess other modifications to trawls used in the CTS and also GABTS. For further information contact Matt Broadhurst on 02 6656 8905.

Testing small-meshed T90 codends in the CTS

In 2020, using funding from the Fisheries Research and Development Corporation and NSW Department of Primary Industries, a four-year project was started that involves working with Commonwealth Trawl Sector (CTS) and Great Australian Bight Trawl Sector (GABTS) fishers to prioritise, assess and then refine modifications designed to reduce unwanted catches and improve trawl efficiencies. Several experiments have been completed, including assessing the effects of: (1) different bobbin disc sizes in the CTS; (2) a square-mesh panel to allow small eastern school whiting to escape inshore trawls; (3) horizontal separator panels in trawls; and (3) four-seam T90 codends (made from 94 to 105 mm mesh) with shortened lastridge ropes (17% shorter and designed to take the catch load off the meshes) in the GABTS.

Most recently, based on the T90 work done in the GABTS, we tested some similar designs of codends on a trawler fishing off Ulladulla in the CTS. We constructed two, four seam T90 codends with shortened Dynema lastridge ropes and 71 mm mesh to match the girth of the smallest legal tiger flathead (28 cm TL) and compared these against a conventional 91-mm diamond-mesh codend (Figs 1 and 2). The only difference between the two T90 codends was the number of meshes around: one was 66% of the stretched diamond-mesh codend circumference (termed 'narrow' 71-mm T90 codend), and the other was 100% ('wide' 71-mm T90 codend; Figs 1 and 2).

During 12–14 tows of each codend, the only significant effects were an increase in the catches of retained latchet by both T90 codends, and greater escape of some small tiger flathead from the wide 71-mm T90 codend than the 91-mm T0 codend. Potentially, a slightly larger mesh (75-80 mm and similar to that used in seines) hung at T90 in a four-seam codend with a wide circumference would provide better selection for tiger flathead than the conventional 90-mm diamond mesh, and without affecting most other catches.

Future work is now being planned to assess other modifications to trawls used in the CTS. For further information contact Matt Broadhurst on 02 6656 8905.

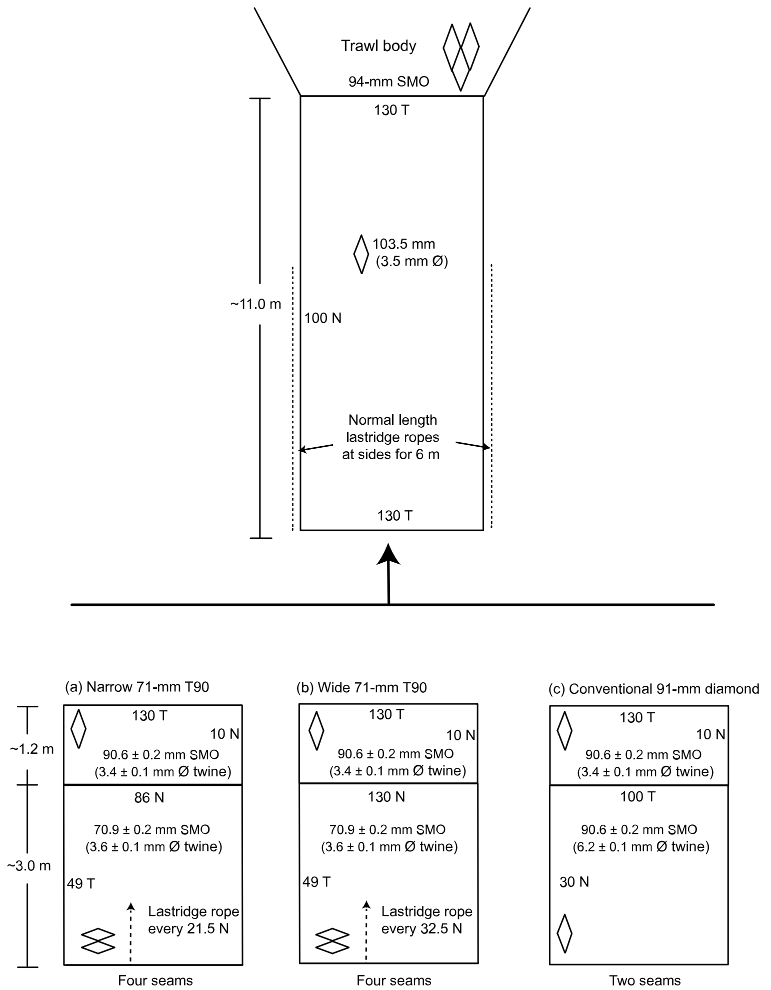

Figure 1. Specifications of the trawl lengthener and (a) narrow and (b) wide 71-mm T90 codends and (c) conventional 91-mm diamond-mesh codend. T, meshes in the transversal (east-west) direction; N, meshes in the normal (north-south) direction; Ø, diameter.

Figure 2. Photograph of the (left) narrow and (middle) wide 71-mm T90 codends and (right) 91-mm diamond-mesh codend.

Effects of headline height on inshore CTS trawls

Four years ago, using funding from the Fisheries Research and Development Corporation and NSW Department of Primary Industries, a project was started that involves working with Commonwealth Trawl Sector (CTS) and Great Australian Bight Trawl Sector (GABTS) fishers to prioritise, assess and then refine modifications designed to reduce unwanted catches and improve trawl efficiencies. The project is nearing its end. Several experiments have been completed, including assessing the effects of: (1) different bobbin disc sizes in the CTS; (2) a square-mesh panel to allow small eastern school whiting to escape NSW inshore trawls; (3) various T90 mesh codend cylinders in the GABTS and CTS; and (4) a horizontal-separator panel in a CTS trawl to investigate where fish orientate during capture.

In multi-species fisheries such as the CTS and GABTS, ideally trawlers would maintain catches of important commercial species (like tiger flathead), while minimising unwanted catches (like skates and rays). To learn more about where these different species orientate in trawls (and possibly suggest future designs for testing), an experiment was done recently in the CTS to investigate the effects of varying headline height on generic trawls. Optimising trawl headline height is very important for any trawl, but the effects can be difficult to isolate owing to variability among other operational or technical factors (such as different spread ratios, ground gears, and/or towing speeds).

We attempted to isolate the effects of headline height by alternately fishing a conventional two-seam CTS trawl (40-m headline length with a mean fishing height of 3.8 m; range of 3.3 to 4.4 m) used inshore to target tiger flathead off Ulladulla and Bermagui with a design that was identical in all key aspects (e.g. ground gear, bridles, sweeps, etc.), but had a ~22% reduction in fishing circumference at the mouth and therefore a similar lower average headline height (2.8 m; range of 2.3 to 3.5 m) (Fig. 1). During 12 days, both trawls were alternately fished for up to 3 h across the same depths (60 to 200 m) and towing speeds (~3 kn) and with the same otter-board spreads (~134 m). We completed 24 and 23 tows of the ‘conventional’ and ‘low’ trawls.

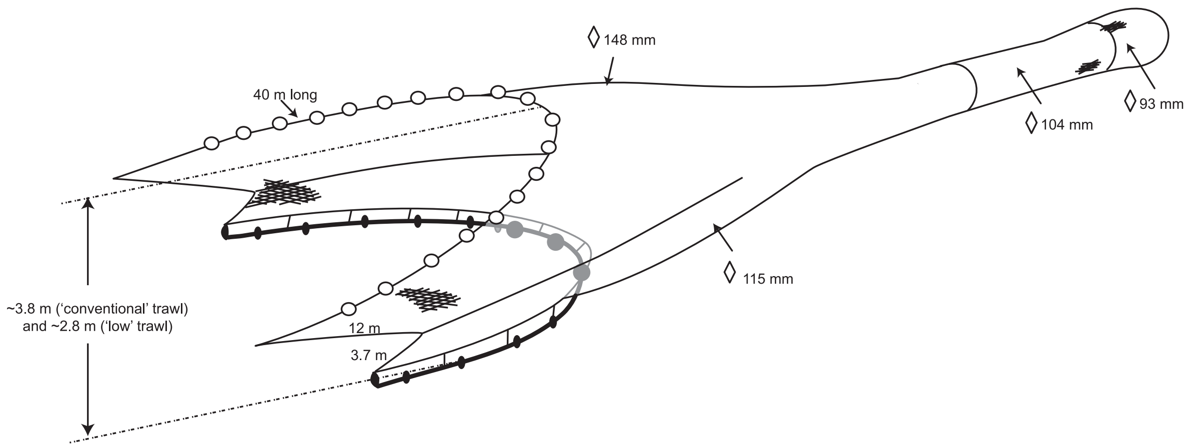

Figure 1. The two tested trawls with average headline heights and general specifications indicated.

The data showed there were no significant differences in the numbers and weights of any retained and discarded species between the two trawls, although the mean catches of the primary target, tiger flathead were lower in the low trawl, implying this species orientates across the range of conventionally fished heights. Regardless of the trawl, there was a significant, the weights of total discards and two abundant ray species (smooth stingray and greenback stingaree) decreased as headline height increased, which was attributed to lower ground-gear contact pressure and/or an increased footrope height of both trawls, possibly allowing the escape of some individuals under the trawl. The only other species affected by headline height was velvet leatherjacket, with catches increasing as headline height increased.

The data suggest that it should be possible to marginally reduce the circumference at the mouth of trawls used to target tiger flathead and so reduce headline height and at least some drag and fuel while maintaining desired catches. More broadly, it appears that regardless of the trawl-body circumference, headline height can indirectly affect species selectivity via effects on other gear components.

For further information contact Matt Broadhurst on 02 6656 8905.

Appendix 18. Legislated permit (NSW) arising from project work (described in Appendix 5).

Fisheries Management (Otter trawl net (fish) codend) Order 2023

under the

Fisheries Management Act 1994

I, PETER TURNELL, Director, Fisheries and Aquaculture with the delegated authority of the Minister and Secretary under sections 227 and 228 of the *Fisheries Management Act 1994* (**the Act**), make this order under section 37 of the Act.

Dated this 20th day of February 2023

PETER TURNELL
Director, Fisheries and Aquaculture
Department of Primary Industries
Department of Regional NSW

Part 1 Preliminary

1 Name of Order

This Order is the *Fisheries Management (Otter trawl net (fish) codend) Order 2023*.

2 Commencement and Duration

This Order commences on the date it is signed and will remain in force until 1 January 2026.

Note: notice of the making of this order will be given by publishing the order on the website of the NSW Department of Regional NSW.

3 Definitions

In this Order:

codend of a net means the piece of netting that forms the posterior most part of the net where the catch accumulates.

extension piece means a section of net that extends from the codend to the wings of the net.

southern fish trawl endorsement holder means a person who holds a commercial fishing licence that has an endorsement that authorises the taking of fish for sale in the southern fish trawl restricted fishery, as defined in clause 3(1) of the Regulation

southern fish trawl restricted fishery is defined in clause 145 of the Regulation

northern fish trawl endorsement holder means a person who holds a commercial fishing licence that has a fish northern zone endorsement that authorises the holder to take fish using an otter trawl net (fish) pursuant to clause 5 of the OT Plan.

Ocean trawl fishing business means a fishing business the components of which include shares in the fishery.

the Act means the *Fisheries Management Act 1994*.

the OT Plan means the *Fisheries Management (Ocean Trawl Share Management Plan) Regulation 2006*

the Regulation means the *Fisheries Management (General) Regulation 2019*.

trawl whiting grounds means the ocean waters west of the ninety (90) metre (45 fathom) depth contour as provided in the *Fisheries Management (Ocean Trawl Fishery Trawl Whiting Grounds) Approval 2021*.

Note: Pursuant to section 11 of the *Interpretation Act 1987*, unless otherwise specified words in this Order have the same meaning as in the Act.

Part 2 Special approval for authorised purposes – northern fish trawl endorsement holder

3 Definitions

In this part:

net means the otter trawl net (fish) as defined in clause 7B of the OT Plan.

4 Modification of the codend in a net

(1) Despite clause 7B of the OT Plan, a northern fish trawl endorsement holder may take fish with a net that has a codend that:

(a) is constructed of diamond-shaped mesh not less than 90 mm, and

(b) includes a section of netting material that:

(i) consists of mesh that is not less than 45 mm, and

(ii) is hung on the bar, so that the mesh is square-shaped, and

(iii) has a width of not more than one quarter of the circumference of the codend or extension piece, and

(iv) has a total cumulative length not more than 5 metres.

5 Use of a modified net in the trawl whiting grounds

The use of a net with a modified codend in accordance clause 4 is only permitted in the trawl whiting grounds.

Part 3 Special approval for authorised purposes – southern fish trawl endorsement holder

6 Definitions

In this part:

net means the otter trawl net (fish) as defined in clause 26 of the Regulation.

7 Modification of the codend in a net

(1) Despite clause 26 of the Regulation, a southern fish trawl endorsement holder may take fish with a net that has a codend that:

(a) is constructed of diamond-shaped mesh not less than 90 mm, and

(b) includes a section of netting material that:

(i) consists of mesh that is not less than 45 mm, and

(ii) is hung on the bar, so that the mesh is square-shaped, and

(iii) has a width of not more than one quarter of the circumference of the codend or extension piece, and

(iv) has a total cumulative length not more than 5 metres

8 Use of a modified net in the southern fish trawl restricted fishery

The use of a net with a modified codend in accordance clause 7 is only permitted in the southern fish trawl restricted fishery.

Note: Other than where expressly stated, this Order does not authorise fishing activities in contravention of the Act or the regulations under the Act.