Reducing the discarding of small prawns in NSW's commercial and recreational prawn fisheries

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Thanks are extended to Drs Steve Kennelly and Charles Gray and our numerous other colleagues at NSW DPI who provided scientific advice and assistance throughout the work and to Dr Russell Millar for his extensive intellectual contribution towards experimental designs and analyses.

NON-TECHNICAL SUMMARY

2001/031	Reducing the discarding of small prawns in NSW's commercial and recreational fisheries

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OBJECTIVES:

(1) To develop and test a variety of modifications to gears and fishing practices that improve size selectivity and reduce the bycatch and discarding of small school and king prawns from the many methods used to catch them in NSW's commercial and recreational fisheries.

(2) To facilitate the extension of the research results throughout the appropriate sectors.

(3) To recommend and help implement appropriate changes to regulations governing these methods to ensure the widespread use of the results.

NON TECHNICAL SUMMARY:

Outcomes Achieved
The project resulted in recommended changes to the majority of prawn-catching gears used throughout NSW's estuaries that will significantly reduce the fishing mortality of non-targeted sizes of prawns and other species. In particular, an increase in the size of the existing diamond mesh (from 20 to between 25 and 30 mm) was recommended for recreational scoop nets, while square-mesh codends made from between 27- and 29-mm knotless polyamide mesh hung on the bar were recommended for most commercial trawls, seines and stow nets. Regulations on key factors other than mesh size that influence efficiency and selectivity were recommended for all gears.

Few fishing gears catch only the targeted species and their sizes, with many selecting a wide diversity of non-target organisms (termed 'bycatch'), causing problematic interactions with other species, fisheries and user groups. During the past 20 years, most of the concerns about bycatch have been directed towards poor species selection by net-based fishing gears (like otter trawls) and the mortality of charismatic species like turtles and dolphins, as well as juveniles of commercially- and recreationally-important fish. In many cases, these concerns have been mitigated via quite simple modifications to fishing gears and practices designed to minimize the fishing mortality of key non-target species. Another key bycatch issue that has received substantially less attention concerns the capture and discarding of individuals of the targeted species smaller than optimal commercial and/or biological sizes. Poor size selection of fishing gears can have obvious effects on the population of the targeted species and, unlike the discarding of non-target bycatch, is of concern to the fishery in question. In New South Wales (NSW) Australia, the discarding of individuals due to inappropriate size selection is a considerable problem throughout many net-based fisheries, and especially those targeting prawns.

Prawns form the basis of important commercial and recreational fisheries throughout NSW. Catches include 6 species, although school (*Metapenaeus macleayi*), eastern king (*Penaeus* *plebejus*), and greasyback prawns (*Metapenaeus bennettae*) account for more than 98% of the total annual commercial (approx. 1000 t) and recreational (approx. 11 million individuals) harvests. These 3 species are targeted throughout estuaries and rivers using 7 types of small-scale fishing gears that include recreational haul, push and scoop nets and commercial otter trawls, seines, stow nets and trap nets.

Like in most Australian fisheries, the 7 prawn-catching gears used in NSW are managed by regulations that include limits on their dimensions, methods, areas of operation and minimum and maximum stretched diamond mesh openings. These legal mesh sizes vary between 40 and 45 mm in the codend (i.e. the bag where the catch is collected) of otter trawls, 30 and 36 mm throughout seines, stow, haul and push nets, 25 and 36 mm throughout trap nets and 20 mm in scoop nets. The use of gears with such small meshes throughout areas that typically have a lot of small fauna has raised considerable concerns and resulted in several quantitative studies of catches. These studies revealed that, at many locations and times most prawn-catching gears, and especially otter trawls, retain small, unwanted prawns (less than between 15 and 17 mm carapace length - CL, or between 2.7 and 3.3 g). Problems associated with the mortality of these individuals and the potentially negative impacts on stocks led to the present study which aimed to determine:

(1) the existing size selectivity (i.e. the proportion of individuals retained for any given size) of the various conventional gears for the key species of prawns; and then, if required

(2) the utility of simple modifications to problematic gears designed to reduce unwanted bycatches of prawns and so improve their size selection.

An underlying assumption of (2) above is that the majority of small prawns escaping through the meshes of fishing gears actually survive the process. However, despite legally-enforced mesh sizes throughout all Australian prawn fisheries, no studies have examined this issue for any of the targeted species. Prior to addressing (1) above, we therefore completed an aquaria-based study that quantified the fate of school prawns after repeated escape from simulated trawls. Like other work done to assess the fate of fish escaping from BRDs, this work demonstrated minimal post-capture damage, stress and mortality (< 11%) and validated an examination of modifications to meshes in prawn-catching gears as a means for reducing the fishing mortality of small prawns.

Where possible, all experiments to assess the size selectivity of the prawn-catching gears were done during normal fishing operations and in those estuaries and rivers characterized by the majority of effort. Each of the experiments involved deploying the gear being tested (termed ‘treatment’) and a fine-meshed ‘control’ gear (either simultaneously or alternatively). The numbers and sizes of prawns (and in some cases non-target bycatch) retained in the treatment and fine-meshed control gear were collected and used to estimate the size selectivity of the treatment gear.

The results from various experiments examining the size selectivity of the 7 conventional gears ((1) above) demonstrated that only trap nets were appropriate in terms of allowing nearly all prawns smaller than optimal commercial sizes to escape. Some small prawns were able to pass through the meshes in recreational haul and push nets and commercial stow nets (rigged with 36-mm diamond-mesh codends), but all other gears were entirely inappropriate and retained large proportions of prawns considerably smaller than optimal sizes, with trawls and some seines demonstrated to be completely non selective (i.e. they retained even the smallest prawns). For these problematic gears, we examined up to 4 modifications designed to increase and regulate the mesh openings in their codends so that small prawns (< 15 mm CL) could escape, but larger, optimal sizes were retained. The modifications involved: (1) reducing the fishing circumference; (2) increasing the size of diamond-shaped mesh; (3) reducing the twine diameter of diamond-shaped mesh; and (4) orientating knotless meshes on the bar, so that they were square shaped.

Experiments examining these modifications for the different gears showed that, irrespective of the size of diamond mesh used, unregulated factors such as the fishing circumference and twine diameter of codends strongly influence the selectivity of prawn-catching gears. While regulating these factors improved the lateral openings of conventional diamond meshes and allowed at least some small prawns to escape, in many cases catches of optimal-sized prawns were also reduced. Appropriate modifications demonstrated to maximize the escape of small unwanted prawns, but maintain catches of optimal sizes, involved:

(1) increasing the existing diamond-shaped mesh from 20 mm to between 25 and 30 mm in recreational scoop nets; and

(2) orientating between 27- and 29-mm knotless mesh on the bar (i.e. square mesh) in the codends of commercial trawls and most seines and stow nets.

While there was considerable variability in selection among these latter gears and their locations, in most cases, compared to the conventional diamond-mesh codends, the square-mesh designs allowed up to 99% of individual sizes of unwanted school prawns and 91% of total fish bycatch to escape, while maintaining commercial catches.

Because the majority of escaping prawns survive, we conclude that if the key factors demonstrated to influence size and species selectivity (such as fishing circumference and twine diameter) are regulated, using 25- to 30-mm diamond-shaped meshes in scoop nets and 27- to 29-mm square-mesh codends in trawls and most stow nets and seines, respectively will significantly reduce the fishing mortality of non-target individuals. An absence of data on the stock status of the key prawn species, or their important life history parameters, means it is difficult to estimate the magnitude of benefits that the recommended modifications will have on populations, but these should translate to at least some improvement in harvests.

KEYWORDS: bycatch reduction, selectivity, penaeids, trawls, stow nets, seines, trap nets, scoop nets, haul nets, push nets

1. INTRODUCTION

1.1. Background

Nearly all commercial and recreational fisheries in Australia are managed by input controls that govern the configurations of the fishing gears used and the practices involved in their deployment. Unfortunately, very few of these regulations, and especially those concerning mesh sizes, are based on any form of scientific assessment; the majority are derived from industry-developed gears and practices that just happened to be common practice when particular fisheries became established (e.g. Broadhurst and Kennelly, 1995). Such historical regulations have become entrenched over time and, in the absence of any scientific information, have proven quite difficult to change.

Commercial and recreational fishing have increased markedly over the past 50 years throughout Australia, with corresponding declines in targeted populations. Because of this, many gear-related fishing regulations are considered to be outdated and lead to significant problems in terms of their selectivity and the capture of undesired organisms (collectively termed 'bycatch' - for reviews see Andrew and Pepperell, 1992, Alverson et al., 1994; Kennelly, 1995). With current requirements to manage fisheries in an ecologically-sustainable fashion, and growing concerns over discarding and wastage, there has emerged a clear need to address the gaps in our knowledge of the most appropriate gears and their configurations that should be used, and accurate descriptions of their selectivities.

Few conventional fishing gears are entirely selective for the targeted species and their sizes, with many retaining a wide diversity of bycatch, causing problematic interactions with other species, fisheries and user groups (Andrew and Pepperell, 1992). The majority of concerns have been directed towards poor species selection and the mortality of non-target species like turtles and dolphins, as well as large quantities of juveniles of commercially- and recreationally-important fish (Andrew and Pepperell, 1992). Another bycatch issue that has received substantially less attention relates to inappropriate size selection and includes the capture, mortality and discarding of conspecifics of the targeted species that are undersize or unsaleable. Such wastage can have obvious effects on populations of the targeted species and, unlike discarding of non-target bycatch, is of paramount concern to the fishery in question.

In Australia, the discarding of individuals conspecific to the targeted species due to poor size selection is a problem throughout many prawn fisheries (Broadhurst et al., 1999a; 2000). Penaeid prawn resources constitute some of the most economically-important commercial and recreational fisheries and their sustainable development partly depends on catching the various species at their optimal sizes. Many of the conventional gears used, however, retain prawns at sizes considerably smaller than those which optimise commercial or biological yield (e.g. Glaister, 1978; Broadhurst and Kennelly, 1996a). This is particularly the case in New South Wales (NSW), where a variety of small-meshed commercial and recreational prawn-catching gears are used throughout estuaries and nearshore areas known to be important nursery grounds for various stocks of prawns. Concerns over the mortality of unwanted juveniles, and the potential for negative impacts on stocks, justified funding for the present study to identify problematic gears in NSW's estuarine prawn fisheries and then examine modifications that improve their size selectivity.

1.2. Need

Penaeid prawns form the basis of several important commercial and recreational fisheries throughout estuaries and rivers in NSW. Catches include 6 species, although school (*Metapenaeus macleyi*), greasyback (*Metapenaeus bennettae*) and eastern king (*Penaeus plebejus*) account for more than 98% of the total annual commercial (approx. 1000 t) and recreational (approx. 11 million individuals - Henry and Lyle, 2003) harvest. These 3 species are targeted throughout their distributions (Coles and Greenwood, 1983) using 7 general types of gear that include recreational haul, push and scoop nets (Fig. 1) and commercial trawls (Fig. 2), seines (Fig. 3), stow nets (Fig. 4) and trap nets (Fig. 5).

Recreational gears have the widest distribution, being permitted throughout more than 120 estuaries and with no temporal restrictions. All gears are hand operated (usually at night) and similar to those used in other Australian states (e.g. Kailoa et al., 1993) and the majority of the world's artisanal penaeid fisheries (Vendeville, 1990). Scoop nets are the most popular recreational gear, used by more than 93% of fishers from boats or close to the shore (with lights) to target prawns swimming near the surface (Montgomery and Reid, 1995). Hauls (used by approx. 6% of fishers) and push nets (< 1% of fishers) are dragged or pulled along the seabed (< 2 m depth), actively directing prawns into their codends. There is little information on the absolute number of recreational prawn fishers in NSW, although Henry and Lyle, (2003) estimated effort at 251 000 fisher hours during 12 months in 1999/2000.

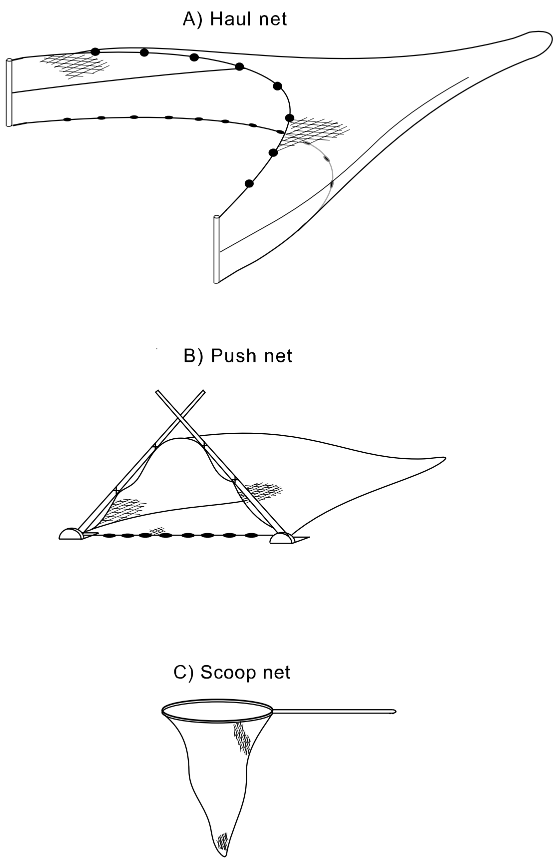

Figure 1. Recreational (A) haul, (B) push and (c) scoop nets used in NSW.

Compared to recreational nets, NSW's commercial prawn-catching gears are considerably more restricted in space and time, with most permitted only during summer (September - May) each year, and in designated locations. Trawls are the most widely-used gear, with up to 240 vessels towing single- and twin-rigged nets (Fig. 2) to mostly target school prawns during the day throughout 4 estuaries (Clarence River - 115 vessels; Hawkesbury River - 65 vessels; Hunter River - 32 vessels and Port Jackson - 30 vessels). Seines are the second most common commercial gear (Fig. 3) and are used by up to 191 fishers to target (1) mostly school prawns in rivers (termed 'hauling') or (2) greasyback prawns and eastern king prawns in coastal lagoons (termed 'snigging'). Although the designs of seines vary slightly among these areas, the basic fishing method involves using anchors, buoys and ropes to set and haul a single net in a semi-circular configuration from small dories (Fig. 3B). Similar in principle to trawls, seines actively direct prawns along the wings and the body of the net and into the codend (Fig. 3B). In contrast to these towed gears, stow (Fig. 4) and trap nets (Fig. 5) are static and catch prawns by exploiting their migratory behaviour within estuaries. These gears are secured to the bottoms of rivers and coastal lagoons using anchors and stanchions and are usually fished at night between the last and first quarter phases of the moon. Stow nets are used to target school and eastern king prawns by up to 180 operators throughout 8 rivers, although more than 82% of the total effort occurs in the Clarence River and Wallis Lake. Prawns and other organisms move into the stationary stow net (which resembles a trawl or short seine) and are washed through to the codend by the flow generated during tidal movements and/or from an anchored vessel's propeller (Fig. 4). Trap nets are used throughout 12 coastal lakes by up to 95 operators (> 40% work in Tuggerah Lakes). All trap nets are similar and comprise a wall of mesh (up to 140 m) secured between a vertical stanchion located near the shore and the horizontal gunwale of a dory anchored on a lake (Fig. 5A). Wind-generated currents cause the netting to assume a parabolic shape, effectively trapping migrating prawns and directing them along the wall of netting towards the horizontally-orientated bunt at the dory. Fishers facilitate this movement of catch by regularly lifting and hauling sections of the trap net over a dory so that it passes underneath the trap net and the catch is rolled towards the bunt (Fig. 5B).

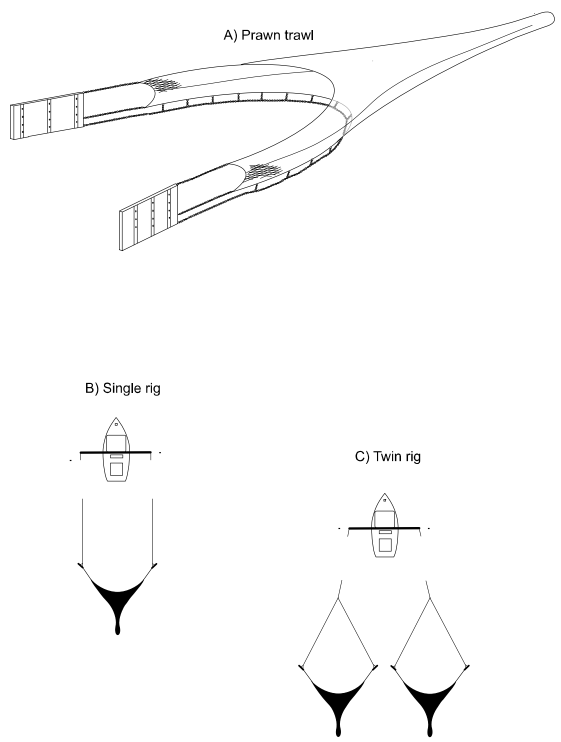

Figure 2. A) typical prawn trawl rigged in B) single and C) twin gear configurations.

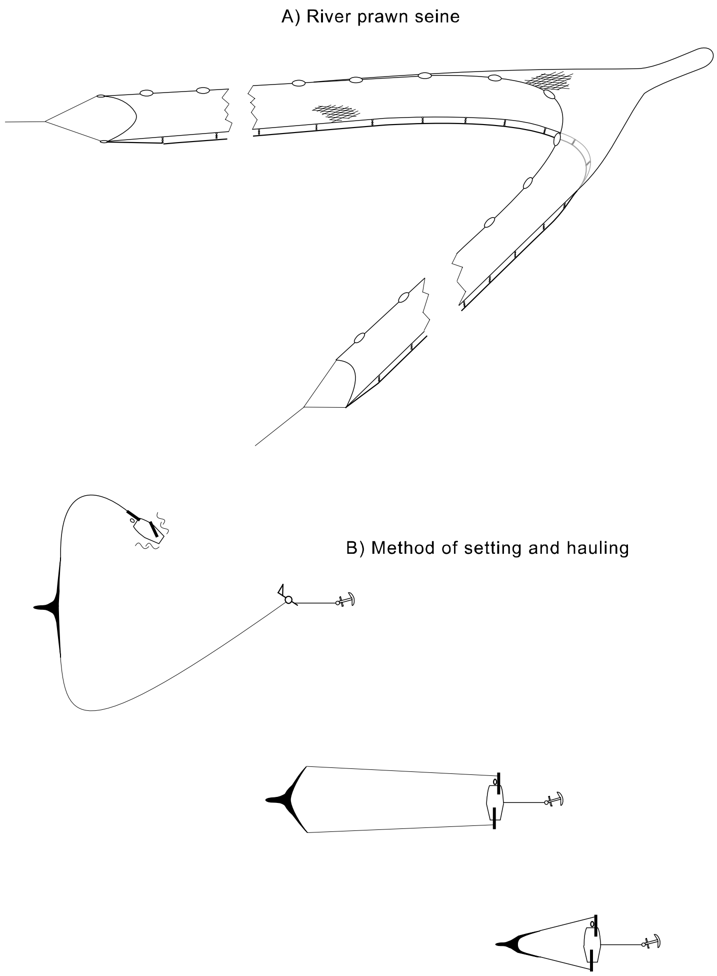

Figure 3. A) river seine and B) method of setting and retrieving the gear.

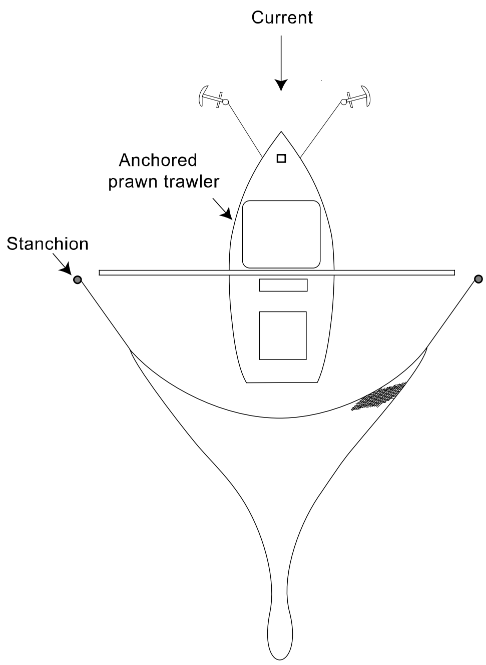

Figure 4. Typical stow net configuration used in NSW.

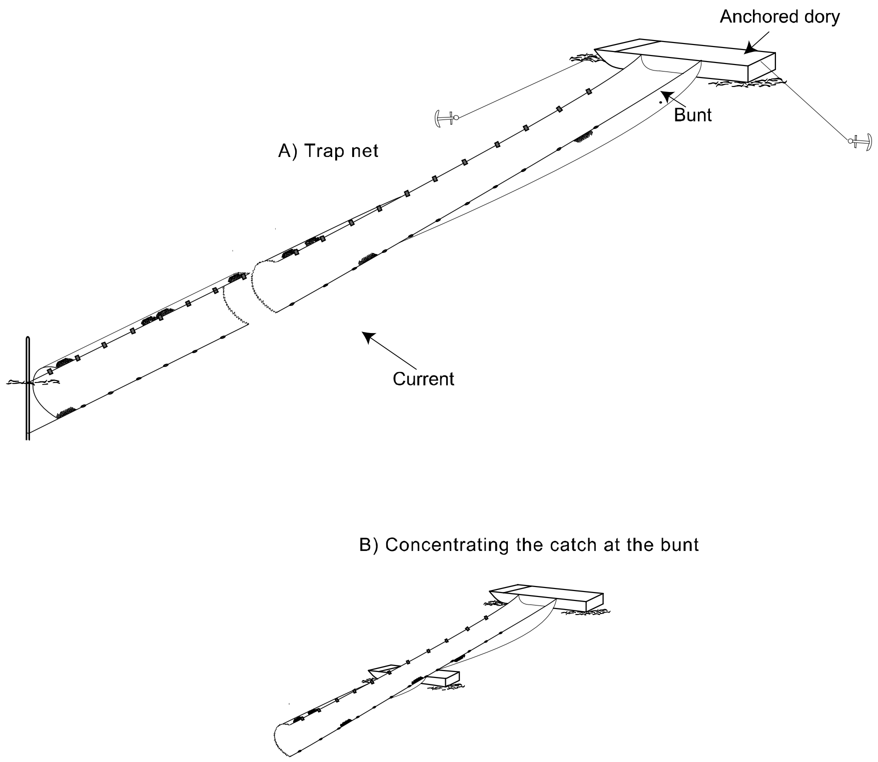

Figure 5. Diagrammatic representation of A) trap nets during fishing and B) using a dory to progressively concentrate the catch towards the bunt.

All of the commercial and recreational prawn-catching gears used in NSW are managed by gear-related input controls that restrict their general dimensions and mesh sizes (measured as inside mesh opening - see Ferro and Xu, 1996 for a definition of mesh measurements). Legal-mesh openings vary between 40 and 45 mm in the codends of trawls, 30 and 36 mm throughout seines, stow, haul and push nets, 25 and 36 mm throughout trap nets and 20 mm for scoop nets. For nearly all gears, fishers generally use the minimum legal mesh size.

Despite the above regulations, there have been no formal estimates of the size selectivity of any gears. Nevertheless, their use throughout habitats that typically are characterized by diverse assemblages and abundances of small fauna (Bell et al., 1988; Gray et al., 1996) has been of concern and resulted in several quantitative studies of catches (e.g. Gray et al., 1990; Andrew et al., 1995; Liggins and Kennelly, 1996; Liggins et al., 1996; Gray, 2001). These studies revealed that at some locations and times, many prawn-catching gears (and especially trawls) retain bycatch that can comprise juveniles of recreationally- and/or commercially-important non-target fish, cephalopods and crustaceans, but nearly always includes small, unwanted conspecifics (< approx. 15-mm carapace length - CL; Fig. 6) of the targeted prawns.

During the past 15 years, concerns over the mortality of bycaught juveniles of recreationally- and commercially-important fish resulted in successful attempts at improving the species selectivity of problematic gears like trawls (e.g. Broadhurst and Kennelly, 1994; 1996a; 1996b; Broadhurst et al., 2004). In the last 5 years, physical modifications to codends (termed bycatch reduction devices - BRDs for a review see Broadhurst, 2000) designed to reduce unwanted catches of fish and other non-target species were legislated for use throughout all prawn-trawl fisheries. In particular, for estuarine trawls, a BRD termed the Nordmøre-grid was demonstrated to mechanically exclude up to 90% of bycatch, with no significant reductions in the catches of prawns (Broadhurst and Kennelly, 1996a).

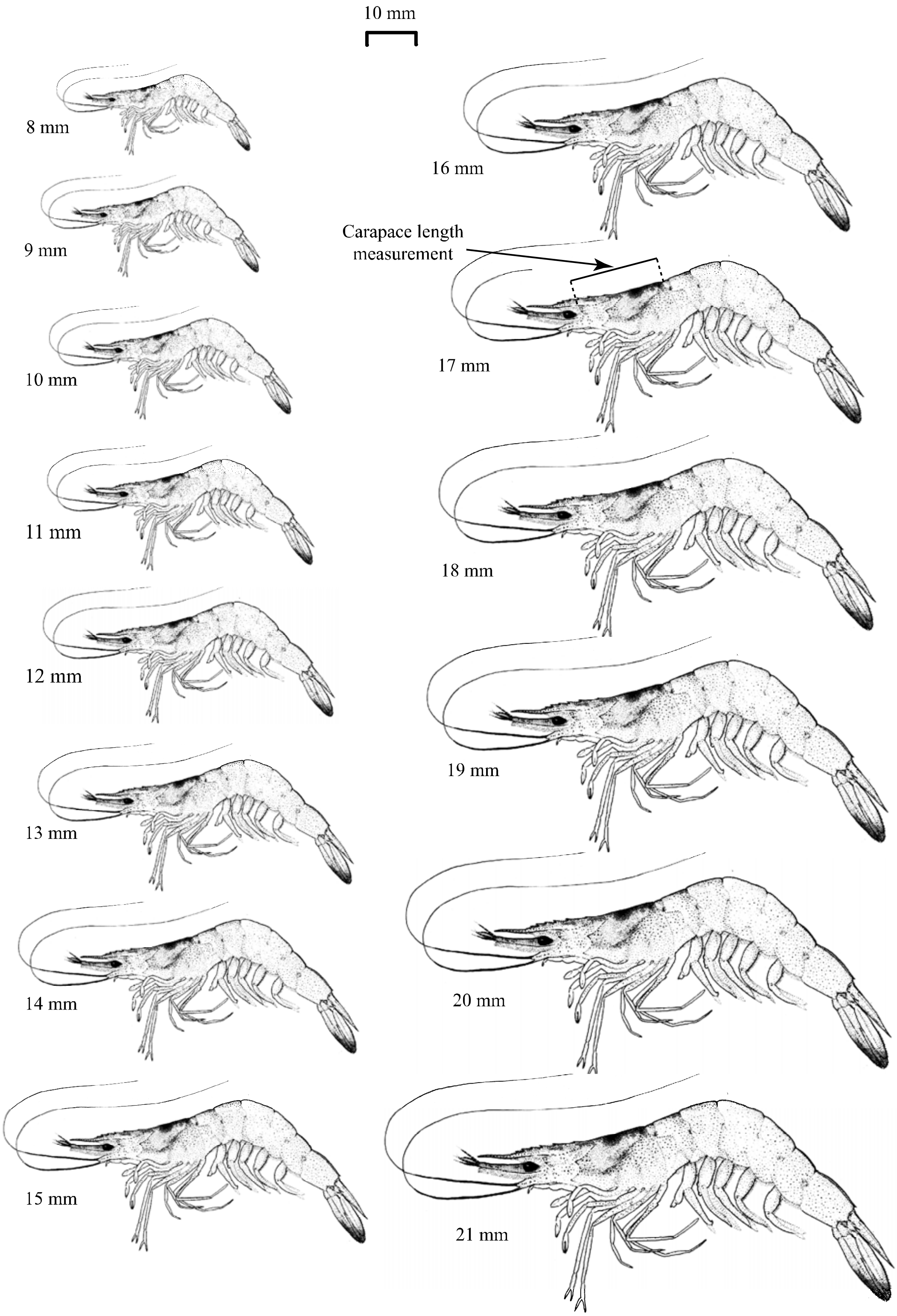

Figure 6. Carapace lengths of school prawns between 8 and 21 mm.

BRDs like the Nordmøre-grid have not been required in other types of commercial or recreational prawn-catching gears because in general, these retain comparably fewer juveniles of important fish and cephalopods. The main bycatch concern for these gears, and a remaining issue for trawl fisheries, is juvenile prawns considered too small for sale. While there is no minimum legal size for any of the prawn species in NSW, operators in most fisheries conform to industry-recommended 'counts' which vary from approx. 150 - 180 prawns 500 g^{-1} (i.e. mean individual weights of 3.3 - 2.7 g or mean CLs of approx. 17 - 15 mm, respectively) (Fig. 6). These 'desired' sizes are similar to the estimated sizes at maturity for school (18 mm CL - Glaister, 1978) and greasyback (> 16 mm CL - Dall, 1958) prawns, but smaller than that for eastern king prawns (34 - 42 mm CL - Glaister, 1983; Courtney et al., 1995). In most fisheries, large numbers of juvenile prawns considerably smaller than 15 mm CL (Broadhurst et al., 1996a) are caught and discarded well after capture through a process of 'riddling' on board the vessel, which involves passing the prawn catch over a sieve to separate large and small individuals. The discarding of small, riddled prawns is considered a major waste of stocks, since their fast growth rates mean that many would be expected to reach commercial size in a short period (Glaister, 1978).

Studies have shown that the size selectivity of funnel-shaped, towed and static fishing gears is influenced by several variables, including the mesh type and size, volume of netting attached to the fishing line (i.e. the hanging ratio), thickness of twine, water velocity during fishing, and even the volume of catch (e.g. Reeves et al., 1992; Lowry and Robertson, 1996; Lök et al., 1997; Broadhurst and Kennelly, 1996b; Broadhurst et al., 2000; Tokaç et al., 2004). These factors combine to ensure that the lateral openings of traditional diamond-shaped meshes in codends or bunts are highly variable, but typically less than between 25 and 35% of the stretched mesh length (Robertson, 1986). For many prawn-catching gears, simple changes to one or more of the gear-related factors listed above, such as an increase in the size of the diamond mesh or the hanging ratio in the codend or bunt (achieved via a reduction in codend circumference), can increase lateral mesh openings and allow more small individuals to escape. One of the simplest methods for increasing and maintaining the lateral mesh openings in codends or bunts across a range of conditions, is to orientate meshes on the bar so that they are square shaped (e.g. Thorsteinsson, 1992; Broadhurst et al., 1999a; 2000). More specifically for trawls, it is apparent that square-shaped mesh between 60 and 100% of the size of the existing, conventional diamond-shaped mesh can allow small prawns to escape, while maintaining commercial catches. These sorts of simple modifications to meshes have been applied in many different trawl fisheries overseas (e.g. Suuronen and Millar, 1992; Thorsteinsson, 1992; Stergiou, 1999) and more recently in an Australian prawn-trawl fishery (Broadhurst et al., 1999a; 2000). For example, in Gulf St. Vincent, Broadhurst et al. (1999a) showed that compared to a conventional diamond-mesh codend, those made entirely with square meshes significantly reduced the bycatch of small western king prawns, (*Penaeus latisulcatus*) (and fish) with no concomitant loss of commercial catch.

The previously successful application of the above modifications to improve the size selectivity of towed fishing gears provides justification for their testing in NSW prawn fisheries. However, an important consideration that has been overlooked in nearly all previous studies involves the fate of escaping organisms. Without estimates of the numbers that survive the process of capture and subsequent escape through codend meshes, it is difficult to quantify any long-term benefits that proposed modifications (or even existing regulations) may have. Therefore, as a prelude to the main body of research in the present study, we examined the effects of multiple capture and escape from the codends of towed gears on the physical damage, stress and mortality of juvenile school prawns. Like previous research done to assess the fate of fish escaping from similar codends (e.g. Broadhurst et al., 1997; 1999b), this work demonstrated minimal post-capture damage, stress and mortality (< 11% - see appendix 3) and validated examining the utility of modifications to meshes in prawn-catching gears as a means for regulating the fishing mortality of juvenile conspecifics.

1.3. Objectives

(1) To develop and test a variety of modifications to gears and fishing practices that improve size selectivity and reduce the bycatch and discarding of small school and king prawns from the many methods used to catch them in NSW's commercial and recreational fisheries.

(2) To facilitate the extension of the research results throughout the appropriate sectors.

(3) To recommend and help implement appropriate changes to regulations governing these methods to ensure the widespread use of the results.

2. METHODS

The first experiment to quantify the fate of school prawns escaping from towed fishing gears (appendix 3) and three experiments to assess the selectivity of recreational gears (appendix 4) were done under controlled conditions in aquaria systems. All other experiments examining conventional and modified gears were done as part of normal commercial operations, using chartered prawn fishers, mostly in those areas characterized by the majority of effort for the particular gears being tested. The justification, materials and methods, analyses and results of all experiments are provided in 10 manuscripts published in international journals and attached as appendices 3 - 12. All of the treatments examined during these experiments are summarized in Table 1.

For many of the gears, four general types of modifications were either directly or indirectly examined for their utility in improving size selectivity. These modifications to codends involved:

(1) increasing the hanging ratio of the posterior section, by reducing the circumference;
(2) increasing the size of the existing diamond-shaped mesh;
(3) reducing the twine diameter of diamond-shaped mesh; and
(4) orientating meshes on the bar so that they were square shaped (Fig. 7).

With respect to (2) above, the codend hanging ratio (E) was defined as:

$$E = \frac{0.35\eta\omega}{\lambda\varphi}$$

where 0.35 is the expected fractional mesh opening of diamond meshes (Broadhurst et al., 1999a) in the extension section or posterior net body; η and ω are the stretched mesh opening (Ferro and Xu, 1996) and number of meshes in circumference, respectively at this location; and λ and φ are the stretched mesh opening and number of meshes in circumference, respectively in the codend.

The selectivities of some modified codends for trawls, seines and stow nets were quantified as part of extension-type work not summarized in the appendices. But, the methods used to test these gears remained the same and followed the general description provided below. Also, to accurately quantify the desired optimal commercial size range of prawns in the Clarence River, we determined the selectivity of a riddler (over 7 replicate deployments). Two estimates were provided that included selection by (i) the riddler alone and (ii) the riddler, plus additional hand grading of prawns by the fisher (as per conventional methods).

2.1. Quantifying the size selectivity of conventional and modified gears

The size selectivity of any fishing gear can be expressed as the species-specific probability of retaining an individual of any given size after it has contacted or entered the gear, independent of the population being fished (Wileman et al., 1996). The selectivity of many towed and static gears that rely on the movement of water during fishing (like all of the various prawn-catching gears used in NSW) is mostly believed to occur in the codend or bunt, where the catch accumulates (Wileman et al., 1996). The size or morphology of individuals in relation to the available mesh openings in this area ultimately determine whether they are retained or escape.

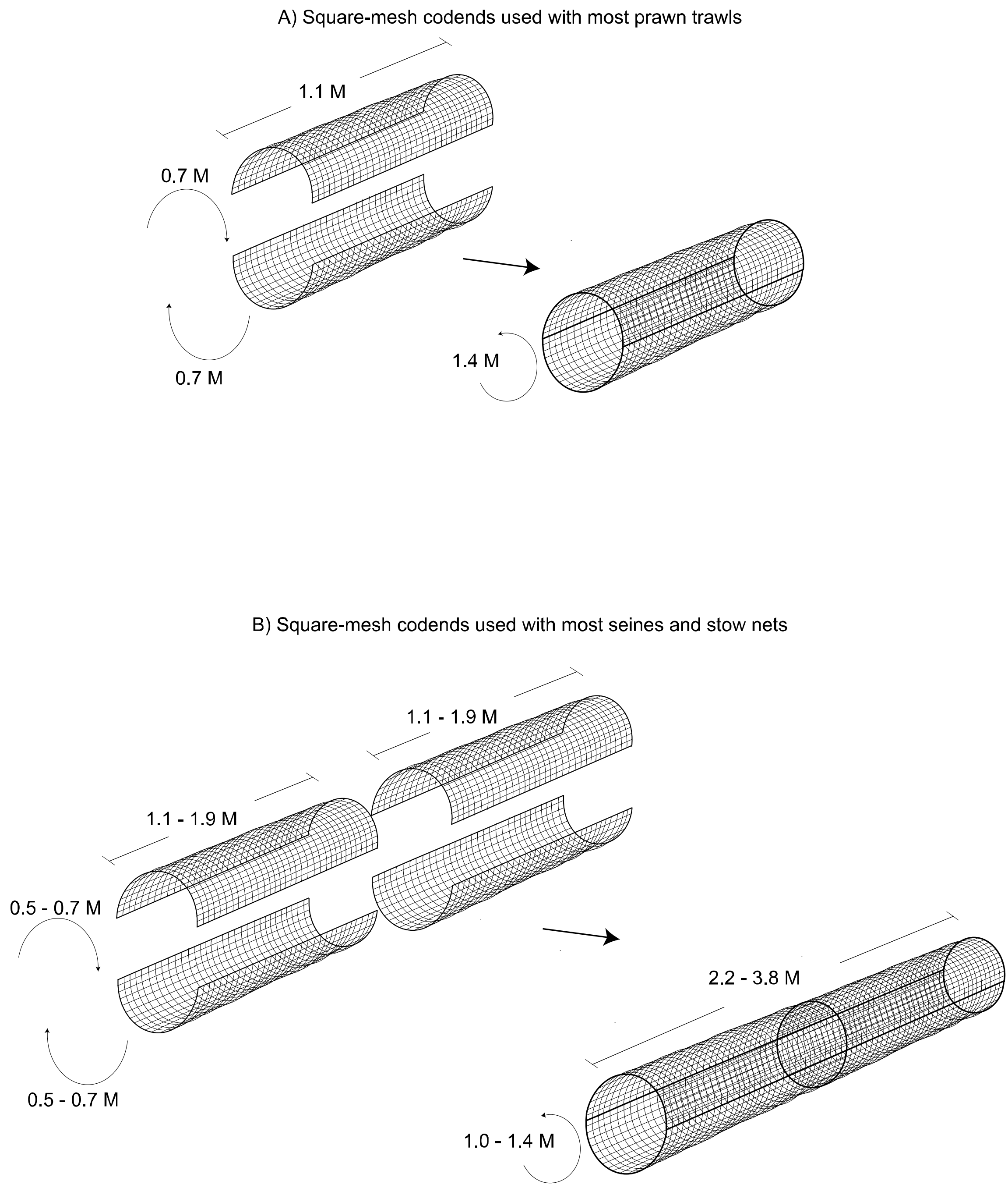

Figure 7. Dimensions of typical square-mesh codends used with A) trawls and B) seines and stow nets.

Three established techniques were used to obtain the data required to estimate the size selectivity of the different gears for prawns (Pope et al., 1975; Wileman et al., 1996). These methods included using a particular conventional or modified (termed 'treatment') and a fine-meshed control gear (usually a codend or bunt): (1) alternately (termed 'alternate haul' - e.g. Broadhurst and Kennelly, 1994); (2) simultaneously in a paired-gear configuration (termed 'paired haul' - e.g. Millar and Walsh, 1992); or (3) in a system where the fine-meshed control was rigged as a cover that retained escapees from the treatment gear (termed 'covered codend' - e.g. Sobrino et al., 2000). In all cases, the fine-meshed control codend, bunt or cover was made from a mesh size and twine diameter approaching 50% of the smallest treatment mesh (Wileman et al., 1996). All conventional fishing gear bodies, treatment codends, bunts and covers were attached to zippers (Burashi S146R) to facilitate attachment and removal. For all gears except trap nets, the length of zippers was based on the expected fishing circumference of the anterior section of a conventional diamond-mesh codend and calculated assuming a fractional mesh opening of 0.35 x the circumference in number of meshes x the stretched mesh length.

In each of the various experiments, all treatment and control gears were fished according to normal conventional practices. At the end of all replicate deployments, data were collected on the numbers, weights and CLs (to the nearest 1 mm) of all prawns, the weights of non-prawn bycatch, the numbers of fish and for some species, their sizes (either fork length - FL or total length - TL to the nearest 5 mm).

The CLs of prawns that were retained and escaped from the various gears and their configurations were incorporated into parametric selection models based on a logistic distribution (characterized by an s-shaped curve or ogive). This type of selectivity curve is summarized by two parameter vectors: the length corresponding to a 50% probability of capture (termed the L_{50}) and the difference in length between the 75 (L_{75}) and 25% (L_{25}) capture probabilities (termed the selection range or SR). Changes to the lateral mesh openings in the codends or bunts of many fishing gears usually have a concomitant effect of either of these two variables. Ideally, when seeking to improve the size selectivity in a particular gear, L_{50} should increase while SR is maintained or reduced.

In most experiments, two competing parametric selection curves were applied (Wileman et al., 1996; Millar and Fryer, 1999). The basic first model (termed the 'logistic curve') is expressed as the following function:

$$P(l) = \frac{\exp(a + bl)}{1 + \exp(a + bl)}$$

where $P(l)$ is the probability that an organism of length l is retained by the gear and a and b are the two parameters to be estimated. This curve is symmetric about the 50% retention length. The selectivity parameter vectors of interest (L_{50} and SR) are derived as:

$$L_{50} = -\frac{a}{b}$$

$$SR = L_{75} - L_{25} = \frac{2\log_e 3}{b}$$

The second model (termed the 'Richard's curve') provides an asymmetric fit, with an additional parameter δ to control the amount of asymmetry (Wileman et al., 1996):

$$P(l) = \left(\frac{\exp(a + bl)}{1 + \exp(a + bl)} \right)^{1/\delta}$$

Table 1. Summary of the gears, locations and the treatments examined during individual fishing operations. [cc]Covered codend experiment; [ph]Paired haul experiment; [ah]Alternate haul experiment; ø, diameter; PA, polyamide; PE, polyethylene; E, hanging ratio of the codend or bunt; n, number of replicate deployments; App, appendix containing a summary of the experiment; --, work done independent of that summarized in the appendices.

Fishing gear	Location	Treatments examined	Treatment material	E	Type of Treatment	*n*	App.
Haul nets	Clarence River (aquaria system)	(cc)30-mm diamond-mesh body / codend	0.4-mm ø, 3-strand knotted PA	1.00	Conventional	8	4
		(cc)30-mm diamond-mesh body with 23-mm square-mesh codend	0.4-mm ø, 3-strand, knotted PA	1.00	Modified	8	4
		(cc)40-mm diamond-mesh body / codend	0.4-mm ø, 3-strand, knotted PA	1.00	Modified	8	4
		(cc)40-mm diamond-mesh body with 23-mm square-mesh codend	0.4-mm ø, 3-strand, knotted PA	1.00	Modified	8	4
Push nets	Clarence River (aquaria system)	(cc)30-mm diamond-mesh net	0.4-mm ø, 3-strand, knotted PA	1.00	Conventional	8	4
		(cc)40-mm diamond-mesh net	0.4-mm ø, 3-strand, knotted PA	1.00	Modified	8	4
		(cc)23-mm square-mesh net	0.4-mm ø, 3-strand, knotted PA	1.00	Modified	8	4
Scoop nets	Clarence River (aquaria system)	(cc)20-mm diamond-mesh net	0.4-mm ø, 3-strand, knotted PA	0.80	Conventional	8	4
		(cc)30-mm diamond-mesh net	0.4-mm ø, 3-strand, knotted PA	0.80	Modified	8	4
		(cc)40-mm diamond-mesh net	0.4-mm ø, 3-strand, knotted PA	0.80	Modified	8	4
		(cc)23-mm square-mesh net	0.4-mm ø, 3-strand, knotted PA	0.80	Modified	8	4
Trawls	Clarence River (including Lake Woolooweyah)	(ph)40-mm diamond-mesh codend	3.0-mm ø, braided, knotted PE	0.18	Conventional	20	5
		(ph)40-mm diamond-mesh codend	3.0-mm ø, braided, knotted PE	0.36	Modified	20	5/6
		(ah)25-mm diamond-mesh codend	0.3-mm ø, 3 strand, knotted PA	0.50	Modified	8	7
		(ph)20-mm square-mesh codend	2.5-mm ø, braided, knotless PA	1.00	Modified	20	5/6
		(ph)20-mm tapered square-mesh codend	2.5-mm ø, braided, knotless PA	1.00	Modified	20	5/6
		(cc)27-mm square-mesh codend	2.2-mm ø, braided, knotless PA	1.00	Modified	6	--
		(cc)27-mm square-mesh codend	2.2-mm ø, braided, knotless PA	1.00	Modified	6	--
		(cc)27-mm square-mesh codend	2.2-mm ø, braided, knotless PA	1.00	Modified	5	--
	Hawkesbury River	(ah)40-mm diamond-mesh codend	3.0-mm ø, braided, knotted PE	0.36	Modified	12	8
		(ah)20-mm square-mesh codend	2.5-mm ø, braided, knotless PA	1.00	Modified	12	8
		(ah)25-mm square-mesh codend	2.2-mm ø, braided, knotless PA	1.00	Modified	12	8
		(cc)27-mm square-mesh codend	2.2-mm ø, braided, knotless PA	1.00	Modified	6	--
		(cc)27-mm square-mesh codend	2.2-mm ø, braided, knotless PA	1.00	Modified	6	--
		(ah)29-mm square-mesh codend	2.2-mm ø, braided, knotless PA	1.00	Modified	12	8
	Hunter River	(cc)27-mm square-mesh codend	2.2-mm ø, braided, knotless PA	1.00	Modified	6	--

Table 1. Continued

Fishing gear	Location	Treatments examined	Treatment material	E	Type of Treatment	*n*	App.
Seines	Richmond River	(ah)30-mm diamond-mesh codend	1.4-mm ø, 3-strand, knotted PE	0.24	Conventional	30	9
		(ah)30-mm diamond-mesh codend	1.4-mm ø, 3-strand, knotted PE	0.36	Conventional	30	9
		(ah)20-mm square-mesh codend	2.5-mm ø, braided, knotless PA	1.00	Modified	30	9
		(ah)25-mm square-mesh codend	2.2-mm ø, braided, knotless PA	1.00	Modified	18	--
		(ah)27-mm square-mesh codend	2.2-mm ø, braided, knotless PA	1.00	Modified	18	--
		(ah)29-mm square-mesh codend	2.2-mm ø, braided, knotless PA	1.00	Modified	18	--
	Smith's Lake	(ah)30-mm diamond-mesh codend	1.4-mm ø, 3-strand, knotted PE	0.36	Conventional	18	9
		(ah)20-mm square-mesh codend	2.5-mm ø, braided, knotless PA	1.00	Modified	18	9
	Wallis Lake	(ah)36-mm diamond-mesh codend	1.5-mm ø, 3-strand, knotted PE	0.33	Modified	15	10
		(ah)25-mm square-mesh codend	2.2-mm ø, braided, knotless PA	1.00	Modified	15	10
		(ah)29-mm square-mesh codend	2.2-mm ø, braided, knotless PA	1.00	Modified	15	10
	Wallamba River	(ah)31-mm diamond-mesh codend	1.5-mm ø, 3-strand, knotted PE	0.33	Conventional	10	10
		(ah)36-mm diamond-mesh codend	1.5-mm ø, 3-strand, knotted PE	0.33	Modified	10	10
		(ah)25-mm square-mesh codend	2.2-mm ø, braided, knotless PA	1.00	Modified	10	10
		(ah)29-mm square-mesh codend	2.2-mm ø, braided, knotless PA	1.00	Modified	10	10
	Clarence River	(ah)25-mm diamond-mesh codend	0.3-mm ø, 3 strand, knotted PA	0.50	Modified	8	7
Stow nets	Clarence River	(cc)30-mm diamond-mesh codend	1.4-mm ø, 3-strand, knotted PE	0.25	Conventional	12	11
		(cc)20-mm square-mesh codend	2.5-mm ø, braided, knotless PA	1.00	Modified	12	11
		(cc)30-mm square-mesh codend	1.4-mm ø, 3-strand, knotted PE	1.00	Modified	12	11
	Wallis Lake	(cc)36-mm diamond-mesh codend	1.5-mm ø, 3-strand, knotted PA	0.21	Conventional	12	10
		(cc)25-mm square-mesh codend	2.4-mm ø, braided, knotless PA	1.00	Modified	12	10
		(cc)29-mm square-mesh codend	2.4-mm ø, braided, knotless PA	1.00	Modified	12	10
Trap nets	Tuggerah Lake	(ah)25-mm diamond-mesh body / bunt	0.4-mm ø, 3 strand, knotted PA 1.2-mm ø, 3 strand, knotted PE	0.50	Conventional	15	12
		(ah)25-mm diamond-mesh body / bunt	0.3-mm ø, 3 strand, knotted PA	0.50	Conventional	14	12
		(ah)25-mm diamond-mesh body with 31-mm bunt	0.3-mm ø, 3 strand, knotted PA	0.50	Modified	14	12
	Clarence River	(ah)25-mm diamond-mesh body / bunt	0.3-mm ø, 3 strand, knotted PA	0.50	Conventional	8	7

The L_{50} and SR are derived as:

$$L_{50} = \frac{\text{logit}(0.5^{\delta}) - a}{b}$$

$$SR = \frac{\text{logit}(0.75^{\delta}) - \text{logit}\,(0.25^{\delta})}{b}$$

The parameters *a*, *b* and, if required, *δ* were estimated by maximum likelihood (Millar and Fryer, 1999) using CC2000 (www.constat.dk) and ttfit and ccfit (free R functions available from www.stat.auckland.ac.nz). For data obtained by alternate- or paired-hauls, model fits used an estimated-split SELECT model (Millar and Walsh, 1992) that included an additional parameter termed the fishing intensity (*p)* or relative fishing efficiency of the treatment gear. This value represents the probability that an individual entered the treatment gear, given that it entered the combined (treatment and control) gear and allows for unequal densities of individuals entering the treatment and control gears (Millar and Walsh, 1992; Millar and Fryer, 1999). Model deviances and the standard errors of parameter estimates were adjusted for over dispersion (due to between-haul variation) using the replicate estimate of dispersion (REP - Millar and Fryer, 1999). The two competing models were assessed by likelihood ratio tests and comparing deviance residuals. Where required, pairwise bivariate Wald statistics (Kotz et al., 1982) were calculated using the estimated parameter vectors of appropriate models to test for differences between the selectivities of treatment modified and conventional gears. These have an approximate chi-square distribution (2 d.f.) under the hypothesis of no differences in the true L_{50}s and SRs of the two gears being compared.

2.2. Quantifying the species selectivity of conventional and modified gears

Although not part of the main objectives of the study, we collected and collated data on the species selectivity of the various gears. In several experiments, nonmetric multivariate and parametric univariate analyses were used to test hypotheses associated with no differences in catches between treatment and control gears. Specific details are included in the attached appendices, although for those experiments where conventional and modified gears were tested simultaneously, a summary of the relative changes in total weights or numbers of bycatch is provided in the Results.

3. RESULTS

More than 5 t of penaeids were caught during the project, with the bulk of the catch comprising school (approx. 86.5%) followed by greasyback (approx. 11%) and eastern king prawns (approx. 2.5%). The individual catches of these species by the various conventional gears were within the ranges of those typically experienced during normal fishing operations, varying between a mean (± se) of 0.2 (0.03) kg per deployment for recreational haul and push nets and 11.85 (2.74) kg per deployment for commercial river seines. Similarly, the rates of non-prawn bycatch per deployment (by conventional gears) were comparable to observations made in previous studies for the relevant fisheries (e.g. Gray et al., 1990; Andrew et al., 1995; Liggins and Kennelly, 1996; Liggins et al., 1996; Gray, 2001) and varied between a mean of 0.28 (0.06) kg for river seines and 1.10 (0.16) kg and 1.15 (0.45) kg for lagoon seines and trap nets, respectively.

Table 2 summarizes the estimated selectivity parameters for all of the conventional (italicised) and modified gears examined during the study. The L_{50} and SR (± se) estimates for the riddler examined in the Clarence River were 12.29 (0.14) and 3.49 (0.12) mm CL, respectively prior to hand grading and 12.40 (0.14) and 2.72 (0.26) mm CL after hand grading. Table 3 includes a summary of changes in non-prawn bycatch by modified gears for those experiments during which conventional and modified gears were tested simultaneously. A general summary of the results for the each of the gears is provided below.

3.1. Haul, push and scoop nets

The selectivities of the existing conventional and up to 3 modified haul, push and scoop nets were quantified (Tables 1 and 2). Logistic selection curves were derived for all treatment nets, with estimated L_{50}s that, for the most part, were slightly larger that the other prawn-catching gears with similar mesh sizes (Table 2). Except for the conventional 20-mm scoop net, all gear configurations had very wide SRs. The conventional 30-mm mesh used in haul and push nets provided appropriate size selection, allowing large proportions of juvenile (< 18 mm CL) and maturing prawns to escape. This observed inherent ‘inefficiency’ in size selection and subsequent escape of at least some proportion of maturing school prawns can be considered a positive attribute of these gears because, unlike commercial gears, they are used with unrestricted effort. In contrast, to the haul and push nets, the conventional 20-mm scoop net had a relatively poor selectivity, retaining all individuals larger than approx. 13 mm CL. Increasing the mesh size of the scoop net to between 25 and 30 mm would widen the SR and significantly improve the probability of some maturing school prawns escaping.

3.2. Trawls

Conventional prawn-trawl codends used throughout NSW’s estuaries are made from 40-mm mesh (3-mm ø braided twine) and comprise a posterior section 200 meshes in circumference attached to a anterior section 100 meshes in circumference (i.e. E = 0.18 - Table 1). In the Clarence River (Lake Woolooweyah), this configuration was demonstrated to be non-selective for school and eastern king prawns, retaining all sizes encountered (e.g. 4 - 21 mm CL). Modifying only the posterior circumference of this codend (by reducing it to 100 meshes or E = 0.36 - Table 1) effectively increased lateral mesh openings and allowed some proportion of small prawns to escape; providing L_{50}s of 8.6 and 10.3 mm and SRs of 3.9 and 3.5 mm for school and eastern king prawns, respectively in Lake Woolooweyah and comparable selectivity for school prawns in the Hawkesbury River (all logistic selection curves - Table 2).

Table 2. Carapace lengths (in mm) at 50% probability of retention (L50) and selection ranges (SR) for school, eastern king and greasyback prawns for conventional (italicized) and modified fishing gears examined in the various estuaries. Standard errors are given in parentheses. NA, no prawns caught; NS, non selective; App., appendix containing a summary of the experiment; --, work done independent of that summarized in the appendices.

Fishing gear and location	**School prawns** L_{50}	**School prawns** SR	**Eastern king prawns** L_{50}	**Eastern king prawns** SR	**Greasyback prawns** L_{50}	**Greasyback prawns** SR	**App.**
Haul nets							
Clarence River (aquaria system)							
30-mm diamond-mesh body / codend	13.42 (0.35)	10.52 (1.39)	NA	NA	NA	NA	4
30-mm diamond-mesh body with 23-mm square-mesh codend	11.65 (0.52)	12.97 (2.01)	NA	NA	NA	NA	4
40-mm diamond-mesh body / codend	18.11 (0.66)	10.44 (1.46)	NA	NA	NA	NA	4
40-mm diamond-mesh body with 23-mm square-mesh codend	16.42 (0.44)	8.36 (1.13)	NA	NA	NA	NA	4
Push nets							
Clarence River (aquaria system)							
30-mm diamond-mesh net	14.58 (0.39)	13.63 (2.18)	NA	NA	NA	NA	4
40-mm diamond-mesh net	20.15 (0.66)	7.73 (0.93)	NA	NA	NA	NA	4
23-mm square-mesh net	13.50 (0.94)	30.68 (11.19)	NA	NA	NA	NA	4
Scoop nets							
Clarence River (aquaria system)							
20-mm diamond-mesh net	7.99 (0.40)	2.47 (0.26)	NA	NA	NA	NA	4
30-mm diamond-mesh net	8.83 (0.86)	7.03 (0.98)	NA	NA	NA	NA	4
40-mm diamond-mesh net	13.07 (0.67)	11.77 (2.38)	NA	NA	NA	NA	4
23-mm square-mesh net	8.25 (0.79)	5.26 (0.70)	NA	NA	NA	NA	4
Otter trawls							
Clarence River (including Lake Woolooweyah)							
40-mm diamond-mesh codend (E = 0.18)	NS	NS	NS	NS	NA	NA	5
40-mm diamond-mesh codend (E = 0.36)	8.60 (0.30)	3.90 (0.06)	10.30 (0.50)	3.50 (0.90)	NA	NA	5/6
25-mm diamond-mesh codend (E = 0.50)	12.02 (0.89)	3.73 (1.12)	NA	NA	NA	NA	7
20-mm square-mesh codend	10.30 (0.20)	3.50 (0.30)	10.60 (0.50)	2.30 (0.50)	NA	NA	5/6
20-mm tapered square-mesh codend	10.10 (0.20)	3.20 (0.30)	10.70 (0.70)	3.50 (1.40)	NA	NA	5/6
27-mm square-mesh codend	12.05 (0.17)	3.56 (0.21)	NA	NA	NA	NA	--
27-mm square-mesh codend	12.23 (0.14)	2.97 (0.18)	NA	NA	NA	NA	--
27-mm square-mesh codend	12.14 (0.20)	3.83 (0.24)	NA	NA	NA	NA	--

Table 2. Continued

Fishing gear and location	School prawns		Eastern king prawns		Greasyback prawns		App.
	L_{50}	SR	L_{50}	SR	L_{50}	SR	
Hawkesbury River							
40-mm diamond-mesh codend (E = 0.36)	10.59 (0.57)	3.42 (1.10)	NA	NA	NA	NA	8
20-mm square-mesh codend	8.90 (0.81)	3.12 (1.66)	NA	NA	NA	NA	8
25-mm square-mesh codend	10.26 (0.65)	3.78 (1.33)	NA	NA	NA	NA	8
27-mm square-mesh codend	10.52 (0.46)	6.71 (1.14)	NA	NA	NA	NA	--
27-mm square-mesh codend	12.96 (0.14)	3.30 (0.31)	NA	NA	NA	NA	--
29-mm square-mesh codend	13.16 (0.53)	4.55 (0.95)	NA	NA	NA	NA	8
Hunter River							
27-mm square-mesh codend	11.94 (0.12)	2.70 (0.14)	NA	NA	NA	NA	--
Seines							
Richmond River							
30-mm diamond-mesh codend (E = 0.24)	7.48 (0.38)	2.72 (0.72)	NA	NA	NA	NA	9
30-mm diamond-mesh codend (E = 0.36)	7.76 (0.37)	2.69 (0.73)	NA	NA	NA	NA	9
20-mm square-mesh codend	10.78 (0.28)	3.71 (0.47)	NA	NA	NA	NA	9
25-mm square-mesh codend	9.69 (0.30)	2.69 (0.51)	NA	NA	NA	NA	--
27-mm square-mesh codend	10.49 (0.25)	2.17 (0.38)	NA	NA	NA	NA	--
29-mm square-mesh codend	11.16 (0.23)	2.68 (0.38)	NA	NA	NA	NA	--
Smith's Lake							
30-mm diamond-mesh codend (E = 0.36)	NA	NA	NA	NA	13.48 (5.09)	13.07 (6.06)	9
20-mm square-mesh codend	NA	NA	NA	NA	13.42 (0.73)	5.84 (0.85)	9
Wallis Lake							
36-mm diamond-mesh codend (E = 0.33)	NA	NA	9.28 (0.50)	2.41 (0.85)	19.43 (12.72)	15.09 (9.81)	10
25-mm square-mesh codend	14.62 (2.48)	2.43 (1.00)	13.60 (0.62)	2.73 (0.51)	12.68 (0.22)	2.24 (0.37)	10
29-mm square-mesh codend	NA	NA	NA	NA	17.70 (1.70)	6.70 (1.40)	10
Wallamba River							
31-mm diamond-mesh codend (E = 0.33)	NS	NS	NA	NA	NA	NA	10
36-mm diamond-mesh codend (E = 0.33)	NS	NS	NA	NA	NA	NA	10
25-mm square-mesh codend	NS	NS	NA	NA	NA	NA	10
29-mm square-mesh codend	7.27 (1.31)	3.70 (2.40)	NA	NA	NA	NA	10
Clarence River (including Lake Woolooweyah)							
25-mm diamond-mesh codend (E = 0.5)	NS	NS	NA	NA	NA	NA	7

Table 2. Continued

Fishing gear and location	School prawns		Eastern king prawns		Greasyback prawns		App.
	L_{50}	SR	L_{50}	SR	L_{50}	SR	
Stow nets							
Clarence River							
30-mm diamond-mesh codend (E = 0.25)	8.46 (1.65)	3.55 (0.86)	8.08 (5.31)	5.11 (5.24)	NA	NA	11
20-mm square-mesh codend	9.68 (1.17)	2.58 (0.64)	11.68 (1.24)	3.03 (1.83)	NA	NA	11
30-mm square-mesh codend	16.05 (0.18)	4.76 (0.57)	16.59 (1.55)	3.35 (2.44)	NA	NA	11
Wallis Lake							
36-mm diamond-mesh codend (E = 0.21)	15.12 (0.30)	5.41 (0.85)	15.20 (0.25)	8.27 (1.15)	NA	NA	10
25-mm square-mesh codend	15.14 (0.23)	3.32 (0.51)	14.41 (0.16)	3.31 (0.20)	NA	NA	10
29-mm square-mesh codend	18.43 (0.27)	3.24 (0.42)	18.07 (0.18)		4.29 (0.27)	NA	NA
Trap nets							
Tuggerah Lake							
25-mm diamond-mesh body / bunt (PA/PE)	NA	NA	21.5 (0.47)	2.23 (0.34)	NA	NA	12
25-mm diamond-mesh body / bunt (PA)	19.42 (0.97)	3.40 (1.15)	19.42 (0.44)	1.90 (0.40)	18.53 (0.30)	2.09 (0.38)	12
25-mm diamond-mesh body with 31-mm bunt	20.70 (1.46)	3.90 (1.55)	24.97 (1.91)	4.36 (0.87)	23.67 (1.58)	4.71 (0.87)	12
Lake Woolooweyah							
25-mm diamond-mesh body / bunt	14.63 (0.37)	1.49 (0.28)	NA	NA	NA	NA	7

Despite having a mesh size almost 40% smaller, a codend made from 25-mm diamond mesh (Table 1) selected school prawns at a greater L_{50} than the 40-mm mesh codend in Lake Woolooweyah, with no difference in the SR (Table 2). This result can be attributed to the relatively narrower twine diameter (e.g. 0.4 vs. 3.0 mm) and greater hanging ratio (e.g. 0.5 vs. 0.36) of the 25-mm diamond-mesh codend (Table 1). These differences would have facilitated greater lateral mesh openings, effectively allowing more small prawns to escape.

Although the above modifications to conventional diamond-mesh codends significantly improved the size selection of prawn trawls, orientating the codend meshes on the bar appeared to provide a more appropriate strategy in terms of consistently increasing L_{50} and, for the most part, maintaining the SR. In the Clarence and Hawkesbury Rivers, incremental increases in the size of square-shaped mesh from 25 to 27 mm in codends (all with a hanging ratio of 1.0 and a twine diameter of approx. 2.2 mm) concomitantly increased L_{50s} from approx. 9 to 13 mm CL (logistic and Richard's curves). In the Clarence and Hunter Rivers, these L_{50s} were associated with SRs mostly less than 3.8 mm, indicating fairly defined selection over a small range of sizes.

The L_{50}s and SRs (± se) of the 27-mm square-mesh codend tested (during extension work) on three trawlers in the Clarence River (Tables 1 and 2) were very similar to those derived from a conventional riddler (12.29 (0.14) and 3.49 (0.12) mm CL, respectively). This result confirmed that the 27-mm square-mesh codend provided the most appropriate selection for commercial sizes in the Clarence River.

Irrespective of the mesh size, all of the square-mesh codends significantly improved species selection of the trawls. For example, compared to the conventional 40-mm diamond-mesh codend used in Lake Woolooweyah, the 20-mm square-mesh codends allowed considerably more small fish (e.g. pink-breasted siphonfish, *Siphamia roseigaster*, whitebait, *Hyperlophus vittatus* and southern herring, *Herklotsichthys castelnaui*) to escape, significantly reducing total bycatch by up to more than 48% (Table 3). Although not directly compared against conventional codends, given their larger mesh size, the 27- and 29-mm square-mesh codends would have augmented the escape of small fish.

3.3. Seines

Seines were characterized by considerable spatial-, temporal- and gear-related variability in the size selection of prawns (Table 2). A key factor contributing to the observed differences involved gear-specific selection mechanisms. More specifically, for all lagoon and some of the river seines examined, the codend appeared to have a major influence on the size selection of prawns. But, for river seines used in the Wallamba River, and a design tested in Lake Woolooweyah, there were no detectable effects on size selectivity associated with changing the mesh in the codend, apart from the escape of some small school prawns by the 29-mm square-mesh codend tested in the Wallamba River (Table 2). This lack of selection for prawns was attributed to a relatively slow towing speed of these river seines (e.g. 0.2 ms^{-1}) compared to the other seines (> 0.5 ms^{-1}), which meant that individuals were not forced into the codend (and selected) until it was lifted on board (see appendix 10 for more details).

In contrast, logistic and Richard's selection curves were successfully converged for conventional diamond-mesh codends (mesh sizes of 30 - 31 mm and E between 0.24 and 0.36) attached to seines in the Richmond River and Smith's Lake (Tables 1 and 2), although like the conventional trawl codends examined above, the corresponding selection parameters were inappropriate for the targeted sizes of prawns. For example, in the Richmond River, two conventional codends (E = 0.24 and 0.36, respectively) similarly selected school prawns at L_{50}s less than 8 mm. While one of these conventional codends retained greasyback prawns at a larger L_{50} in Smith's Lake (13.48 mm), this selection was highly variable and occurred across an SR of more than 13 mm; corresponding to a substantial loss of commercial-sized individuals. Increasing the size of diamond-shaped mesh to 36 mm in Wallis Lake increased the L_{50} for greasyback prawns to 19.43 mm, but maintained a similar, unacceptably wide SR (e.g. 15.09 mm - Table 2).

Table 3. Mean percentage differences in total non-prawn bycatch by modified fishing gears tested during comparative trials with conventional gears. [cc]covered-codend experiment; [ph]paired-haul experiment; [ah]alternate-haul experiment; NA, no data available; ↓, reduction by modified gear; ↑, increase by modified gear; App., appendix containing a summary of the experiment; [ns]non-significant; *significant ($P < 0.05$); **significant ($P < 0.01$).

Modified fishing gear and location tested	% difference in bycatch no.	% difference in bycatch wt	App.
Commercial			
Otter trawls			
Clarence River (Lake Woolooweyah)			
(ph)40-mm diamond-mesh codend (E = 0.36)	NA	30.80*↓	5
(ph)20-mm square-mesh codend	NA	50.89*↓	5
(ph)20-mm tapered square-mesh codend	NA	48.52*↓	5
Seines			
Richmond River			
(ah)20-mm square-mesh codend	10.13[ns]↑	6.81[ns]↑	9
Smith’s Lake			
(ah)20-mm square-mesh codend	35.91**↓	9.52[ns]↓	9
Wallis Lake			
(ah)25-mm square-mesh codend	57.71*↓	NA	10
(ah)29-mm square-mesh codend	69.84*↓	NA	10
Wallamba River			
(ah)36-mm diamond-mesh codend	12.84[ns]↓	NA	10
(ah)25-mm square-mesh codend	25.94[ns]↓	NA	10
(ah)29-mm square-mesh codend	51.63[ns]↓	NA	10
Stow nets			
Clarence River			
(cc)20-mm square-mesh codend	29.90*↓	8.83*↓	11
(cc)30-mm square-mesh codend	54.78*↓	15.24*↓	11
Wallis Lake			
(cc)25-mm square-mesh codend	76.74*↓	NA	10
(cc)29-mm square-mesh codend	91.34*↓	NA	10

Like the trawls examined above, square-mesh codends significantly improved size and species selection in Richmond River and Smith’s and Wallis Lake seines (Table 2). Not withstanding the considerable temporal- and gear-related variabilities in performance among these three areas, codends made from mesh sizes between 25 and 29 mm hung on the bar incrementally increased L_{50}s for prawns and, in the majority of cases, maintained SRs at less than 3 mm (Table 2). These modified codends also significantly improved species selection in most of the seines, reducing the numbers of small fish like pink-breasted siphonfish and whitebait and the total numbers of bycatch by up to almost 70% (Table 3).

3.4. Stow nets

Stow nets were examined in the Clarence River and Wallis Lake (Tables 1 and 2). Like seines and trawls, the selectivities of the conventional 30-mm diamond-mesh codend in the Clarence River was inappropriate for the targeted sizes of school and eastern king prawns (Table 2). In Wallis Lake, a larger diamond-mesh codend (36-mm mesh) significantly increased the L_{50}s for school and eastern king prawns, but with concomitant increases in SR (up to 8 mm). Square-mesh codends made from between 25- and 29-mm mesh hung on the bar achieved similar or better L_{50}s, while either reducing or maintaining SRs - except for the 30-mm square-mesh codend tested in the Clarence River. This latter codend had an inflated SR that was attributed to its narrow twine diameter and the material used in its construction. Unlike the other square-mesh designs, this codend was made from knotted polyethylene - PE (1.4 mm twine ø - Table 1) and many of the meshes were observed to be distorted at the end of fishing. This would have allowed varying sizes of prawns to escape and contributed to selection across a wide range of CLs (i.e. a SR of 4.76 mm - Table 2). Like the towed gears examined above, compared to the conventional codends, the various square-mesh designs significantly reduced the numbers of bycatch by up to 91%.

3.5. Trap nets

Despite having the smallest mesh size of all conventional commercial prawn-catching gears used in NSW, trap nets selected prawns at L_{50}s (between approx. 14.5 and 23.5 mm) that were up to 2.5 times greater (Table 2). Further, this selection occurred across a narrower range of sizes (Table 2). In Tuggerah Lakes, the observed L_{50}s meant that the majority of all prawns less than between 18 and 20 mm CL escaped. Increasing the mesh size in the bunt to 31 mm increased the L_{50}s, but at some loss of commercial-sized prawns. This result, combined with the appropriate selectivity of the conventional 25-mm net, precluded any further examination of modifications to trap nets.

4. DISCUSSION

Of the 7 gears examined, the commercial trap nets provided the most appropriate size selection, retaining prawns at L_{50}s larger than the estimated sizes at maturity of school and greasyback prawns (18 and > 16 mm CL) and the approx. mean optimal commercial sizes of between 15 and 17 mm CL. The recreational haul and push nets and commercial Wallis Lake stow nets (rigged with 36-mm diamond-mesh codends) did select school prawns at L_{50}s approaching these sizes, although their inflated SRs meant that at least some proportion of small individuals were retained. All other conventionally-rigged gears were entirely inappropriate, being either non-selective or retaining prawns less than 8 mm CL.

The considerable disparity in size selection between the various conventional gear types mostly can be attributed to their different geometries and methods of operation. For the trap net, hauling the headline and foot rope of the entire posterior section of the gear over the dory (Fig. 5B) spread large transverse sections of the netting (i.e. > 3 m) and maintained mesh openings at an area where the catch was dispersed and being progressively rolled towards the bunt. By facilitating multiple contacts between all prawns and the open meshes, this process provided numerous opportunities for selection to occur throughout the body of the net. Similarly, owing to their light construction (e.g. 0.4-mm ø twine), low volume of netting and steep body tapers, the recreational haul and push nets had relatively wide lateral mesh openings throughout their wings, bodies and codends. These characteristics and the slow hauling speed (e.g. 0.15 ms^{-1}) meant that, irrespective of their CL, many school prawns had a high probability of encountering the open meshes in the anterior sections of the gear and being selected.

In contrast to the commercial trap net and recreational haul and push nets, most size selection in the various trawls, stow nets and seines appeared to occur in the codend. The only observed exceptions were some river seines (e.g. in the Wallamba River) which, like the recreational haul and push nets, were hauled very slowly (0.2 ms^{-1}) and selected prawns only in their wings and bodies. In all other gears, the relative water velocity (typically between 0.5 and 2.5 ms^{-1}) meant that prawns were quickly forced into the codend, where the majority of meshes were orientated parallel to the direction of flow. This would have effectively limited the opportunity for small prawns to randomly contact meshes. More importantly, however, like in many penaeid fisheries throughout the world, conventional codends in NSW's prawn fisheries are made with low hanging ratios (i.e. large volumes of mesh relative to the expected fishing circumference) and knotted mesh, often made from thick twine (Vendeville, 1990; Broadhurst and Kennelly, 1996a). These characteristics substantially reduce the lateral openings of diamond meshes; to the point where even if small prawns do contact the sides of the codend, they are unable to escape.

The extent to which hanging ratio negatively affected selection was clearly demonstrated in Clarence River trawls, where an increase from the conventional 0.18 to a modified 0.36 (corresponding to a reduction in posterior codend circumference from 200 to 100 meshes - appendix 5) significantly improved the selectivity of a 40-mm diamond-mesh codend (Table 2 - see also Broadhurst and Kennelly, 1996b). Further, despite a reduction in mesh size by almost 40%, a concomitant increase in hanging ratio to 0.5 in the 25-mm diamond-mesh codend meant that school prawns were selected at an L_{50} 1.4 times larger than the 40-mm codend described above. This occurred because the larger hanging ratio in the 25-mm diamond-mesh codend allowed the meshes to spread laterally, providing more openings for small school prawns to pass through. These observations clearly demonstrate the dominating influence that hanging ratio has on size selection in codends (irrespective of the size of mesh) and how a simple reduction in the volume of netting can significantly improve mesh openings and allow small prawns to escape.

Increasing the size of the conventional diamond mesh, while maintaining hanging ratio at between approx. 0.33 and 0.36, also increased the L_{50} for seines, but this selection occurred over a wide range of sizes. For example, an increase in diamond mesh from 30 to 36 mm in Smith's and Wallis Lake seines increased the L_{50} for greasyback prawns from 13.48 to 19.43 mm CL, but the SR was greater than 15 mm (Table 2). A similar voluntary increase in mesh size by Wallis Lake stownetters meant that school and eastern king prawns were selected across SRs of 5.4 and 8.27 mm CL, respectively (Table 2). Such wide size selection can be explained by the influences of various gear and operational factors on the lateral openings of diamond-shaped meshes and the morphology of the targeted prawns. During fishing, the weight of the catch in the codend, towing speed and even the presence or absence of weed, all combine to ensure that the fractional openings of diamond meshes fluctuate and select varying proportions of different-sized prawns. In the worst case scenario, the maximum lateral opening of a 35 mm mesh would be sufficient to allow the majority of prawns caught in NSW's estuaries to escape. This is illustrated by the linear regressions in Figure 7 which show that school prawns with a CL of 24 mm have a MW and MH less than 16 mm; sufficient to pass through an open 35-mm mesh. Although diamond-shaped meshes are unlikely to fully open in the codend during fishing, even small fluctuations translate to varying proportions of different sizes of prawns being retained and are reflected in the inflated SRs observed for the above trawls, seines and stow nets.

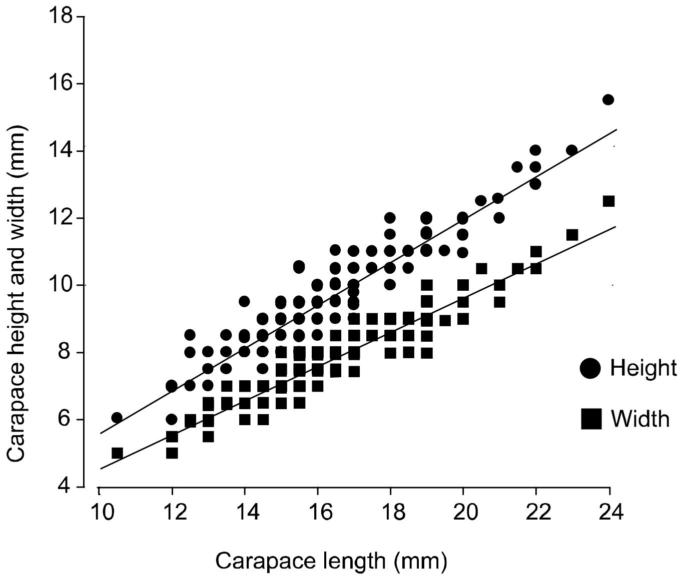

Figure 8. Linear regressions between the carapace length and maximum height and width for school prawns (n = 200).

Given the above, it would seem that an appropriate strategy for selecting prawns at defined sizes would be to consistently maintain mesh openings at a size and shape larger than the relevant transverse morphology of the targeted individuals. The 25-mm diamond-mesh codend examined in the Clarence River demonstrated that one way of approaching this is to simply reduce the size of conventional diamond mesh and then attempt to open these meshes by increasing the hanging ratio (to at least 0.5). But, while this sort of modification was demonstrated to increase the L_{50}, the inherent characteristics of diamond-shaped mesh mean that the potential still remains for some variability in selection. This is supported by the comparatively large standard error associated with the estimated SR for the 25-mm diamond-mesh codend (Table 2) and the inflated SRs for the 30- and 40-mm scoop nets; which were hung at E = 0.8. In contrast, orientating meshes on the bar at their maximum hanging ratio (so that they were square shaped) tends to minimize much of the variability in mesh openings and, for many of the problematic gears, this strategy appeared to facilitate a more defined selection.

Although there were considerable fishery- and gear-specific variabilities in performances, compared to conventional diamond-mesh codends, those made from square-shaped mesh between 20 and 29 mm allowed significantly more small prawns and fish to escape from all trawls, stow nets and most seines, thereby significantly improving their size and species selectivity. In particular, the 27-mm square-mesh codend attached to trawls and most seines allowed large numbers of small organisms to escape while selecting school prawns at L_{50}s between approx. 10.5 and 13 mm CL and across SRs mostly less than 3.85 mm. These selectivity parameters are close to those estimated for riddlers in the Clarence River and translate to significant reductions in the catches of small, unwanted prawns. An example of the extent of these reductions is provided in Table 4 where the largest L_{50} and smallest SR estimates for the riddler and the 27-mm square-mesh codend used in the Clarence River were used to calculate the percentage of prawns escaping for all sizes between 5 and 20 mm CL. The size selection of the 27-mm square-mesh codend was very similar to that provided by the riddling process and allowed between 21 and 99% of small, unwanted school prawns to escape during fishing with minimal loss of commercial-sized individuals (i.e. > 15 mm CL - Table 4).

Table 4. Estimated percentages of school prawns between 5 and 20 mm carapace length (CL) escaping from the conventional 40-mm diamond-mesh codend (non selective), being 'riddled' from the landed catch (using an L50 and SR of 12.40 and 2.72 mm CL, respectively) onboard the vessel or escaping from the 27-mm square-mesh codend (using an L50 and SR of 12.23 and 2.97 mm CL, respectively) during fishing in the Clarence River. Unwanted sizes of prawns and their % reductions are marked in bold.

CL (mm)	Percentage of school prawns passing through the		
	conventional 40-mm diamond-mesh codend	on board riddler	27-mm square- mesh codend
5	0.00	99.75	99.53
6	0.00	99.44	99.01
7	0.00	98.75	97.95
8	0.00	97.24	95.81
9	0.00	94.01	91.60
10	0.00	87.49	83.88
11	0.00	75.69	71.30
12	0.00	58.10	54.24
13	0.00	38.18	36.13
14	0.00	21.57	21.26
15	0.00	10.91	11.41
16	0.00	5.17	5.79
17	0.00	2.37	2.85
18	0.00	1.07	1.38
19	0.00	0.48	0.66
20	0.00	0.21	0.32

Unlike the other modifications to codends examined, the different sizes of square-shaped mesh (all made from approx. 2.2 mm ø, knotless polyaminde mesh) mostly showed a positive correlation with L_{50}, while the SRs were generally maintained at less than 4 mm (Table 2). The exceptions were for trawls in the Hawkesbury River and seines in Wallis and Smith's lakes, where large quantities of weed may have masked the meshes and prevented some small prawns from escaping (effectively inflating the SRs - Table 2). For most other gears and locations, this general trend of increasing L_{50} and maintenance of SR is important because it means that size selection can at least be partly regulated according to spatial-, temporal- and even species-specific differences in the optimal targeted sizes of prawns. For example, while trawlers in the Clarence River mostly retain school prawns > 15 mm CL, those in the Hunter and Hawkesbury Rivers target sizes > 17 mm CL. For these latter estuaries, a mesh size approaching 29 mm hung on the bar might be more appropriate than 27 mm.

Given that the majority of small school prawns that encounter and escape through codend meshes apparently survive the process, the use of square-mesh codends in trawls, stow nets and most seines is likely to significantly reduce their fishing mortality. In the absence of information on the stock status of the key species, or important life history parameters, such as growth and natural mortality, it is difficult to quantify any short- or long-term effects that such modifications will have on stocks of prawns or bycatch species. Nevertheless, the adoption of simple and inexpensive square mesh codends by relevant prawn fishers seems an appropriate, precautionary management strategy.

5. IMPLICATIONS OF THE RESEARCH

5.1. Benefits

This study has provided the first formal estimates of the size selectivity of prawn-catching gears used throughout NSW and demonstrated that, except for recreational haul and push nets and commercial trap nets and some stow nets, all other gears are inappropriately configured for the targeted sizes of prawns. Simple modifications involving changing the size and configuration of meshes were demonstrated to significantly improve both size and species selectivity. For recreational scoop nets, increasing the existing mesh size from 20 to 30 mm while maintaining hanging ratio at 0.8 allowed some proportion of juvenile school prawns to escape. For many commercial trawls, stow nets and seines, the use of mesh between 27 and 29 mm hung on the bar (square shaped) allowed large proportions of small prawns (< 15 mm CL) to escape, with no significant reduction in the catches of commercial-sized individuals. The results from an experiment done to determine the fate of school prawns after escaping from trawl codends suggest that majority of these escaping individuals sustain minimal physical damage and mortality (i.e. < 11%).

Given the above, the wide scale use of modifications like square-mesh codends throughout NSW's commercial prawn trawls, stow nets and most seines is likely to positively contribute towards stocks of prawns, although in the absence of accurate estimates of growth and natural mortality of the key species (school prawns) it is difficult to quantify these benefits. Regardless of this, allowing large numbers of juvenile prawns to remain alive in areas where they are known to be important prey for many recreationally- and commercially-important fish mght be expected to have some positive benefit on stocks of these species.

The operational benefits of using square-mesh codends include:

(1) up to a 40% reduction in the cost of netting;
(2) savings in fuel for trawls and seines, owing to improved water flow and less drag;
(3) improved quality of prawns due to less abrasion from knotless PA netting; and
(4) reduced sorting times.

The realization of these benefits by participants in various commercial industries resulted in the wide scale, voluntary adoption (>150 operators across all fisheries) of the recommended square-mesh codends.

5.2. Further Developments

The project confirmed previous work done in NSW (e.g. Broadhurst and Kennelly, 1996b) which showed that factors other than mesh size, and especially hanging ratio, strongly influence the selectivity of codends - irrespective of the mesh size. Some of the other sorts of important factors demonstrated to influence both the size and species selection of towed gears include the twine diameter (Lowry and Robertson, 1992; Broadhurst et al., 2000) and material (e.g. Tokaç, et al. 2004), body taper (e.g. Broadhurst et al., 2000) and codend length (e.g. Reeves et al., 1992). Given the results presented here, and the likely influence of these other factors on selection, it is apparent that the historical emphasis on regulating mainly the mesh sizes of NSW prawn-catching gears (and other types of towed gears throughout Australia) is entirely insufficient to effectively control their exploitation rate and the fishing mortality of non-target species and sizes. Future developments would benefit from some formal quantification of the influences of the above sorts of factors on the selectivity and efficiency of other key gears (e.g. fish trawls and seines). This will facilitate appropriate restrictions as part of management regulations.

It is also likely that because similar sizes and configurations of the conventional diamond-shaped mesh used in NSW prawn fisheries are used throughout Australia (but see Broadhurst et al., 1999a; 2000) to target penaeids considerably larger in size than those recorded in the present study, these fisheries would benefit from an examination of similar sorts of modifications tested here.

5.3. Planned Outcomes

The planned outcomes for this project were to:

(1) improve catches of prawns in NSW’s many commercial and recreational fisheries for these species;
(2) improve the knowledge on the gear types and fishing practices in these fisheries and how to study, test and improve them;
(3) improve public perception of commercial fishing practices for prawns;
(4) increase efficiencies for commercial fishers via reductions in sorting times;
(5) improve the quality of seafood; and
(6) improve relationships among NSW DPI, industry and the recreational sector via their participation in the project and the projects’s extension phase.

In the short term, it is difficult to quantify the extent to which catches of prawns will be improved by the use of the modified gears. It is likely, however, that a wide scale reduction in the fishing mortality of large proportions of juvenile prawns will have some long-term, measurable benefit in terms of improved stocks, which should correspond to improved harvests. With respect to outcome 2 above, the publications in the attached appendices provide evidence of the contribution of the project towards the advancement of knowledge about the prawn gears used in NSW and methods for determining their selectivity. Satisfaction of outcomes 4, 5 and 6 above is evidenced by the wide scale voluntary adoption of the modified gears by NSW fishing industries. Such adoption reflects a commitment by many industries to promote sustainable fishing practices. A result of this adoption is an improved public perception of commercial fishing for prawns (3 above).

5.4. Conclusions

The project demonstrated that:

(1) the size selectivities of most existing conventional prawn-catching gears used in NSW are entirely inappropriate for the targeted prawns;
(2) several unregulated factors, and especially hanging ratio and twine diameter, strongly influence the selectivity of these gears, irrespective of mesh size;
(3) providing factors like hanging ratio and twine diameter are regulated, codends made from mesh between 27 and 29 mm hung on the bar (square mesh) will significantly improve the size and species selectivity of most prawn trawls, seines and stow nets, while diamond-shaped mesh between 25 and 30 mm will improve the selectivity of scoop nets; and
(4) because the majority of prawns escaping though meshes appear to survive the process, the wide scale use of modified prawn-catching gears will reduce the fishing mortality of non target conspecifics and other species.

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APPENDICES

Appendix 1 - Intellectual Property

The intellectual property owned by FRDC as specified in the agreed contract is 63.85%, although no specific commercial value was derived in terms of patents or copyrights.

Appendix 2 - Staff

Staff that worked on the project using funds from NSW DPI:
Dr Matt Broadhurst
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Appendix 3 - Broadhurst, M.K., Barker, D.T., Paterson, B.D. and Kennelly, S.J. 2002. Fate of juvenile school prawns, *Metapenaeus macleayi*, after simulated capture and escape from trawls. Mar. Freshwater Res. 53: 1189-1196.

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Fate of juvenile school prawns, *Metapenaeus macleayi*, after simulated capture and escape from trawls

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Abstract. Two laboratory experiments were done to assess the fate of juvenile school prawns, *Metapenaeus macleayi*, after simulated multiple capture and escape from trawls. In the first experiment, prawns that were trawled and escaped one, five or 10 times, sustained some physical damage (mostly limited to the loss of antennae), but this was not significantly different from that sustained by control prawns that had not been trawled. Similarly, there were no significant differences between the different treatments and control prawns in their stress levels (as measured by changes in concentrations of L-lactate). Levels of L-lactate were greatest in all prawns immediately after the experiment started and then significantly reduced after 24 and 48 h. In the second experiment, treated prawns were trawled and escaped 10 times and then monitored for mortalities over 2 weeks. Compared with control prawns (that were not trawled), significantly more treated prawns died at the end of the 2 weeks, but the overall post-trawl survival rate was >89%. It is concluded that the multiple contact and escape of juvenile school prawns from trawls had minimal effect on their overall condition.

Extra keywords: by-catch, mesh size, mortality, penaeid, stress.

Introduction

Prawn trawling occurs in four estuaries in New South Wales, Australia, and is valued at approximately AU$7 million per annum. Operators working in these fisheries mainly target school prawns, *Metapenaeus macleayi*, and, like the majority of prawn-trawl fisheries throughout the world, they also catch non-target organisms (termed by-catch; for reviews see Saila 1983; Andrew and Pepperell 1992; Alverson *et al.* 1994), comprising various small crustaceans, cephalopods and fish, which are usually discarded (Liggins and Kennelly 1996; Liggins *et al.* 1996). Over the past decade, various modifications to trawls (termed by-catch reduction devices) have been developed and legislated to improve selectivity and reduce by-catches of fish (for a review see Broadhurst 2000). An important issue that remains, however, involves the capture, discarding and subsequent mortality of small unwanted school prawns.

There is no minimum legal size for school prawns in New South Wales, although operators in most fisheries conform to industry-recommended 'counts', which can vary up to approximately 150 to 180 prawns/500 g (i.e. mean weight of 3.3 to 2.7 g or mean carapace length (CL) of approx. 17 to 15 mm respectively). No formal studies have been done to quantify the selectivities of the minimum legal mesh sizes used in commercial trawls in New South Wales (45 mm in the trawl body and 40 mm in the codend), but it is apparent that large numbers of prawns smaller than the optimal size (i.e. <15 mm CL) are caught (Broadhurst and Kennelly 1996; Broadhurst *et al.* 1996) and then discarded. This is considered to be a major waste of prawn stocks, particularly since these small prawns could be expected to reach commercial size in a relatively short period of time (Glaister 1978).

It is well established that one of the simplest options for reducing unwanted by-catches of organisms that are conspecific to the targeted species in trawls, involves increasing openings in the codend, via alterations to the hanging ratio, size and/or shape of the meshes (e.g. MacLennan 1992; Reeves *et al.* 1992; Broadhurst *et al.* 1999). However, less information is available on the benefits

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of these sorts of changes for prawn-trawl fisheries, since there has been very little quantification of the fate of those prawns that enter trawls and then escape. Such assessments should precede attempts to improve selectivity because, unless a large proportion of escapees survive, simple modifications to gears will have little benefit in preserving stocks. Further, in fisheries that have high densities of trawling effort across small spatial and temporal scales (as is the case in the New South Wales estuarine prawn-trawl fisheries; Liggins *et al.* 1996), small prawns are likely to repeatedly contact trawls and so these assessments should include an examination of the effects of multiple contact and escape.

Studies have shown that many variables affect the damage and mortality of organisms that contact and escape from trawls (Kaiser and Spencer 1995; Chopin *et al.* 1996). For many organisms, sublethal disruptions and physical trauma can be cumulative and may contribute to longer-term mortalities (e.g. via an increased susceptibility to pathogens). One method of quantifying the severity of stress incurred by escaping crustaceans is to determine lactic acid concentrations in their haemolymph. The typical escape response of crustaceans to trawls involves repeated abdominal contractions that propel the animal backwards (Newland *et al.* 1992). This activity uses reserves of arginine phosphate in the abdominal muscle (Onnen and Zebe 1983), which is then anaerobically replenished through glycolysis. This process leads to the accumulation of lactic acid, which must be cleared when activity returns to normal. Measuring the concentration of lactate and reductions over time can therefore provide some indication of the severity of stress.

Because of the need to determine the benefits that any changes in the meshes used in trawls may have on stocks of school prawns, our aim in this study was to provide a first examination of the effects of repeated capture and escape on their physical damage, stress and mortality.

Materials and methods

Equipment used

Two experiments were done at the Cronulla Fisheries Centre's aquarium facilities between September and November 2001 using two 4000-L fibreglass holding tanks and 25 smaller fibreglass tanks (200 L). All tanks were supplied with seawater (at ambient temperature, approx. 18°C) at a rate of 2 L min^{-1}, aerated using air–stone diffusers and equipped with outflow pipes (Fig. 1*a*), designed to maintain constant water levels. The smaller tanks contained 600 g of sand substratum (Fig. 1*a*) and were evenly distributed on opposite sides of an enclosed room with a regulated 12:12-h photoperiod.

Two identical aluminium frames were constructed so that they could be inserted over each of the outflow pipes in the smaller tanks and fit between the inside wall of the tank and the outside wall of the outflow pipe (Fig. 1*b*). The first frame was rigged with a loose panel of mesh (3-mm diameter braided polyethylene twine, 40-mm stretched mesh between the knots) and designed to represent the posterior section of a trawl codend. Links of 40-mm galvanized metal chain (the same size as that used in the footropes of commercial trawls) were attached around the perimeter of this frame (Fig. 1*b*). The second frame was rigged with a tightly hung panel of the same-sized mesh as that described above attached anterior to a panel of fine-meshed polyethylene designed to prevent prawns from passing through (Fig. 1*b*). The two aluminium frames could be placed along side each other and rotated freely throughout the entire volume of the 200-L tanks (Fig. 1*c*).

Collection of prawns

Approximately 2500 juvenile school prawns (<20 mm CL) were captured in the Hawkesbury River (33°42S, 151°15E) using a prawn trawl rigged with a fine-meshed codend (knotless nylon, 10-mm mesh size) towed for less than 20 min in shallow water (depths of between 6 and 12 m). At the end of each tow, the codend was emptied onto a sorting container. Live juvenile school prawns were removed, placed in holding tanks on the vessel and supplied with oxygen. These prawns were transported to the aquarium facility at the Cronulla Fisheries Centre and transferred (using buckets) to the 4000-L holding tanks. Prawns were allowed to acclimatize in the large holding tanks for at least 8 days, during which they were fed a diet of commercial fish pellets (at a rate of approximately 5% of their biomass every second day). All dead prawns were immediately removed and recorded.

Experiment 1: analyses of physical damage and L-lactate after one, five and 10 trawls

Eight days after the prawns were captured (by which time all mortalities had stopped), the water level in one holding tank was lowered (to approx. 1000 L) and ice added to reduce the temperature to 12°C. This effectively anaesthetized the prawns. Two hundred and fifty prawns were selected at random, visually checked for signs of obvious physical damage (any damaged prawns were discarded) and placed in groups of 10 into each of the 25 smaller tanks (in the enclosed room). Because there was no evidence of any sexual dimorphism in the length/weight relationship of school prawns (see Results), individuals were randomly placed in tanks irrespective of their sex. These prawns were fed, monitored and left to acclimatize for a further 5 days. At the end of this period, 24 of the tanks were randomly assigned into four groups (three treatment groups and one control group) each with six replicate tanks. To maintain stocking densities throughout the experiments, prawns in the remaining tank (stock tank) were used to replace any mortalities in the treatment and control tanks. These prawns were marked for identification by cutting one uropod and excluded from all analyses.

On the first day of this experiment, the two aluminium frames were placed in the six tanks in treatment Group 1 and the frame with the 40-mm mesh and chain was rotated around each tank (Fig. 1*c*), so that all 10 prawns in each tank entered this panel and then passed through the meshes. To simulate repeated episodes of trawling and escape, this methodology was applied to the tanks in the remaining treatment groups and then repeated (with 3 min between successive 'trawls') five times in the six tanks holding treatment Group 2, and 10 times in the six tanks holding treatment Group 3. All of the control tanks simply had the two aluminium frames inserted and then removed without contacting any of the prawns.

At periods of 2 min, 24 and 48 h after the various procedures were done in the tanks, all prawns were removed from two randomly selected tanks in each of the three treatment groups and the control group (i.e. 10 prawns from two replicate tanks from each group after each period) using a scoop net. To restrict the activity of the prawns, they were removed along with a sufficient quantity of the sandy substratum in which they were buried.

Four randomly selected prawns from each tank were immediately secured in labelled aluminium satchels and kept frozen in liquid nitrogen for lactate analyses. Because of the significant costs involved, analyses of L-lactate were only done for three of these frozen prawns. Each of these prawns was ground to a homogenous powder in a mortar

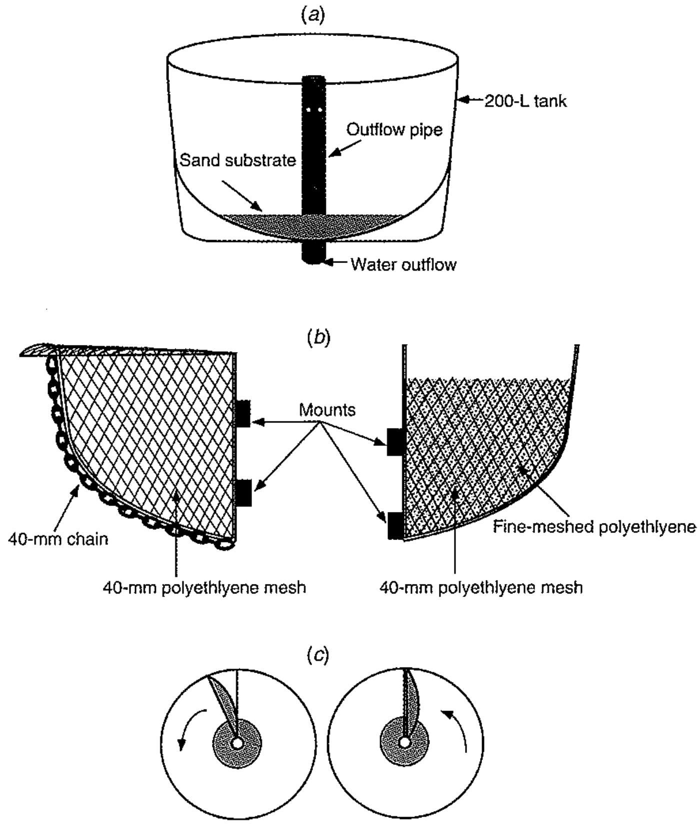

Fig. 1. Diagrammatic representation of: (*a*) the 200-L fibreglass tanks; (*b*) the aluminium frames and panels used in the experiments; and (*c*) the frames being rotated together in the treatment tanks.

that was pre-cooled with liquid nitrogen. Approximately 150 mg of the frozen, powdered tissue was then rapidly dispersed in 1.5 mL of 0.3 M perchloric acid in a 2-mL plastic centrifuge tube (by vortex mixing) and reweighed to determine the tissue mass. Each tissue-perchlorate suspension was centrifuged at 10000*g* for 10 min to compact the protein debris, and 1.5 mL of the supernatant was transferred to a new tube and kept frozen until neutralization. For neutralization, 1 mL of supernatant was added to 0.1 mL of 2 M $KHCO_3$ in a 2-mL plastic centrifuge tube, vortex-mixed and left on ice to allow the crystals to settle. The L-lactate concentration in each extract was determined spectrophotometrically using a Boehringer kit (Cat. no. 139 084) and a 200 mg L^{-1} L-lactate standard. The L-lactate concentration in each extracted prawn sample was calculated after correcting for dilution during neutralization and expressed in terms of μmol g^{-1} of the homogenized prawn sample. The moisture content contributed by the sample to the extract volume after centrifugation was determined to be 71% of the sample weight.

Five of the remaining prawns from each tank were weighed, measured and visually assessed for physical trauma to their exoskeletons. Physical trauma was expressed in terms of percentage damage or loss (to the nearest 5%) for a total of 20 variables (Fig. 2). With the exception of the rostrum and telson, all variables were examined on both sides of the prawns, and the means of these values were calculated to provide estimates of the damage for each variable. To provide an indication of total physical trauma for each prawn, we calculated the percentage of all 20 variables that showed evidence of any damage.

Experiment 2: analysis of mortality after 10 trawls

Experiment 2 was done immediately after Experiment 1 was completed. All prawns in the second 4000-L holding tank were anaesthetized as above. Two hundred were selected at random, individually checked for any signs of physical damage, removed and placed in groups of eight into each of the 25 smaller tanks. These prawns were fed and monitored as above and left to acclimatize for a further 5 days. At the end of this period, 24 tanks were labelled either as treatment or control tanks (i.e. 12 of each), and one was labelled as a stock tank.

The two aluminium frames were placed in all of the 12 treatment tanks and the frame with the 40-mm mesh panel and chain was rotated around each tank (as per the methodology described above). This was repeated 10 times (with 3 min between successive 'trawls'). All control

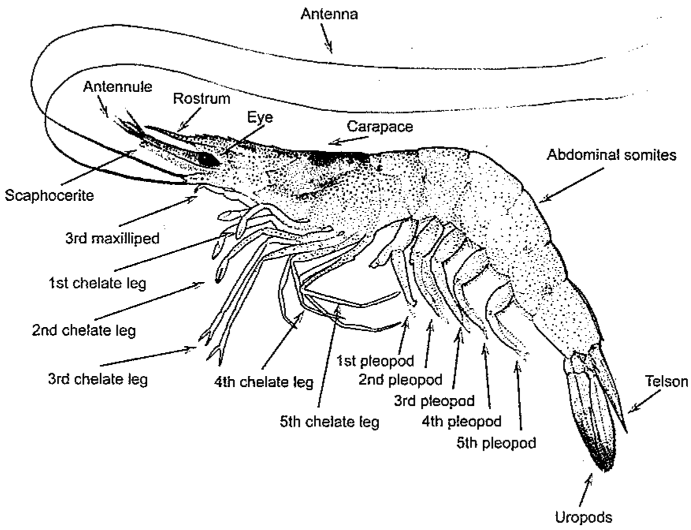

Fig. 2. Profile of a school prawn and the variables used to estimate physical damage.

tanks simply had the mesh panels inserted once and then removed without contacting any prawns. Over a period of 14 days, the prawns in all tanks were monitored twice daily for any mortalities. Where mortalities were detected, all dead individuals were removed from their tanks and replaced with the same number of live prawns (marked for identification by cutting one uropod) from the stock tank.

Statistical analyses

Using all available data, linear regressions of weight (g) and CL (mm) were calculated separately for males and females and then compared using the appropriate analysis of co-variance (this was done *a priori* to test the hypothesis of no sexual dimorphism). Two-sample Kolmogorov–Smirnov tests (P = 0.05) were used to compare the size-frequencies of prawns (pooled across sexes) between experiments.

In Experiment 1, where there were sufficient data for the various indicators of trauma (i.e. percentage physical damage and L-lactate concentrations), the appropriate ANOVA was used (Underwood 1981). In these analyses, the treatment (of prawns) and time (of sampling) were considered fixed factors and orthogonal to each other. Tanks were random (nested in treatment and time) and the data obtained from the randomly selected prawns per tank per sample time were the replicates. To increase the power of the test for the main effect of the treatment of prawns, where the F-ratio for tanks was non-significant at $P < 0.25$, the means squares for tanks and the residual were pooled to provide a new F-ratio denominator (Winer 1971). Significant differences detected in these analyses were investigated using Student–Newman–Keuls multiple comparisons.

The percentages of prawns surviving at the end of Experiment 2 (over 14 days) in each of the treatment and control tanks were calculated and compared using two-tailed t-tests. It was not possible to record mortalities over a shorter temporal scale (e.g. daily), because as individuals died, they were quickly consumed by the remaining individuals in the tanks (i.e. dead prawns disappeared before they could be counted). To examine the effects of repeated trawling on the growth of prawns, the CL and weight of a random sample of remaining prawns (six from each tank) at the end of Experiment 2 were analysed using the appropriate ANOVA. In these analyses, tanks were considered a random factor nested in the treatment of prawns and the six prawns per tank were the replicates. In doing these analyses, we assumed that since there were no significant differences in the weight/length relationship between sexes (see Results) and all prawns were originally placed at random in each of the 200-L tanks (randomly assigned as either treatment or controls), the mean sizes of prawns in each of the tanks at the start of the experiment were the same.

Results

Prawns used in experiments

Approximately 900 of the 2500 prawns collected and placed in the 4000-L holding tanks died (97% of these mortalities occurred within 6 days of collection). Five prawns died (three as a result of jumping from tanks) during the acclimatizing period in the 200-L tanks for Experiment 1. There were no mortalities during the acclimatizing period for Experiment 2.

The sizes of prawns ranged from 8 to 19 mm CL and their distributions were not significantly different between experiments (Kolmogorov–Smirnov test). Analysis of co-variance failed to detect significant differences in regression coefficients (F = 0.40, P > 0.05) or elevations (F = 0.05, P > 0.05) between the regressions of logWt and logCL for males (logWt = 2.8859logCL – 6.816, r^2 = 0.874, n = 331) and females (logWt = 2.9395logCL – 6.958, r^2 = 0.897, n = 140). A common regression was therefore calculated as logWt = 2.9045logCL – 6.8658.

Experiment 1: analyses of physical damage and L-lactate after one, five and 10 trawls

Four prawns died within 4 h of the various treatments being done. Two of these mortalities occurred in tanks from

Table 1. Experiment 1: summary of the physical damage to the four prawns that died within 4 h

Prawn no.	Treatment group	Carapace length (mm)	Weight (g)	Variable and percentage missing
1	Trawled once	16	2.8	Antenna (left): 80%; rostrum: 100% ; scaphocerite (left): fifth chelete leg (left): 10%
2	Trawled five times	15	2.9	Antenna (left): 80%; antenna (right): 20%
3	Trawled five times	14	2.7	Antenna (left): 20%; antenna (right): 20%
4	Trawled 10 times	16	2.7	Antenna (left): 100%; antenna (right): 100%; antennule (left): 20%; antennule (right): 20%; scaphocerite (left): 10%; scaphocerite (right): 10%; second chelete leg (left): 100%

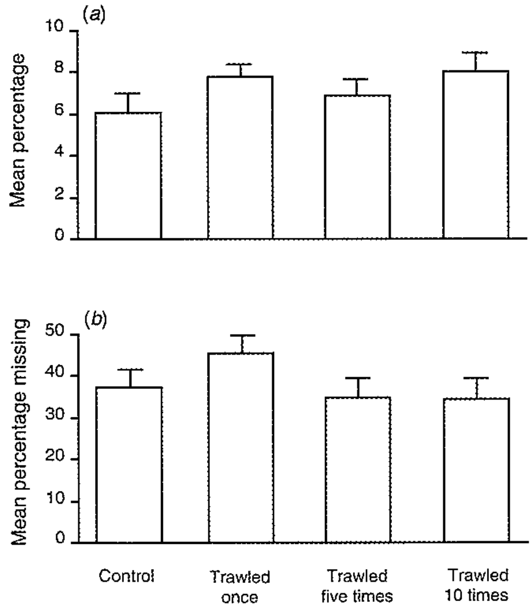

Fig. 3. Differences in mean percentage damage + 1 s.e. between the control and treatment prawns in Experiment 1 for: (*a*) total damage; and (*b*) antennae.

treatment Group 2 (trawled five times) and one each in tanks from treatment Groups 1 (trawled once) and 3 (trawled 10 times). Table 1 summarizes the physical damage sustained by these individuals. There were no mortalities in any of the control tanks.

Three samples of tissue (from prawns in different tanks) yielded results for L-lactate concentrations that were considered impossible (e.g. one negative and two outlying values) and attributed to errors incurred during processing. These values were substituted with the appropriate cell means and 3 df subtracted from the residual df. Subsequent ANOVA revealed that there were no significant differences for the main effect of treatment of prawns for levels of L-lactate or physical damage (Fig. 3; Table 2). A significant effect of time after treatment was detected for L-lactate (Table 2) with Student–Newman–Keuls tests revealing that mean levels were elevated in all prawns at the 2-min sample time (mean ± s.e. = 7.78 ± 0.5 μmol g^{-1}) and then significantly lower at the 24-h (5.21 ± 0.36 μmol g^{-1}) and 48-h sample times (3.72 ± 0.32 μmol g^{-1}) (Fig. 4).

Experiment 2: analysis of mortality after being trawled 10 times

Significantly more prawns died in treatment tanks (12 individuals from seven tanks) than in control tanks (two individuals from two tanks) (t-value = –2.8, $P < 0.05$), providing an overall mortality rate of rate of 10.7% for prawns that were trawled and then escaped 10 times. The majority of dead individuals were at least partially consumed by the remaining prawns in the tanks, precluding any assessment of their physical damage. There were no significant differences detected between treatment and control prawns for their CL or weight at the end of this experiment (Table 3).

Discussion

Overall, the results from this study showed that juvenile school prawns sustained minimal damage, stress and mortality after multiple contact and escape from simulated trawls. These results support the current use of minimum mesh sizes as a management tool to minimize the fishing mortality of small, unwanted school prawns and provide justification for future studies that seek to improve trawl selectivity via modifications to increase mesh openings.

In Experiment 1, the physical damage sustained by prawns was not significantly different between the control and the various treatments (total mean damage ranged from 6% to 8%; Fig. 3*a*) and was limited mostly to the loss of antennae (mean reductions between 34.5% and 45.4%; Fig. 3*b*). These results imply that the effects on prawns as a result of confinement within the tanks were no different to the effects of the simulated trawling, regardless of the number of 'trawls' (i.e. one, five or 10). This result may be explained by the behaviour of prawns during their contact and escape from the simulated trawl. Before starting Experiment 1, all prawns were buried in the sandy

Table 2. Experiment 1: summaries of *F*-ratios from ANOVA to determine effects on damage and stress of prawns as a result of different treatments (i.e. control prawns compared with prawns that were trawled one, five and 10 times), time (after treatment) and tanks, and of Student–Newman–Keuls tests for the significant *F*-ratio for L-lactate detected for the effect of time

*$P < 0.05$; **$P < 0.01$. Residual df were 96 and 45 for physical variables and L-lactate respectively. Pld indicates that the main effect for tanks was non-significant at $P < 0.25$ and the sums of squares pooled with the residual. df for the *F*-test for the main effect of treatment of prawns when tanks were pooled = 3, 108. L-lactate data were ln(x + 1) transformed. 2-min sample time > 24-h sample time > 48-h sample time

Source of variation	df	Total physical damage	Antennae	L-lactate (μmol g^{-1})
Treatment of prawns (TP)	3	1.29	0.77	2.24
Time (T)	2	2.96	0.93	14.84**
T × TP	6	1.73	0.32	0.43
Tanks	12	0.99^{pld}	1.83	2.41*

Table 3. Experiment 2: summaries of *F*-ratios from ANOVA to determine effects on the growth of prawns after 14 days as a result of different treatments (i.e. control prawns compared with prawns that were trawled 10 times) and tanks

Pld indicates that the main effect for tanks was non-significant at $P < 0.25$ and the sums of squares pooled with the residual; df for the *F*-test for the main effect of treatment of prawns when tanks were pooled = 1, 144

Source of variation	df	Carapace length (mm)	Weight (g)
Treatment of prawns	1	1.11	2.15
Tanks	22	0.72^{pld}	0.59^{pld}
Residual	120		

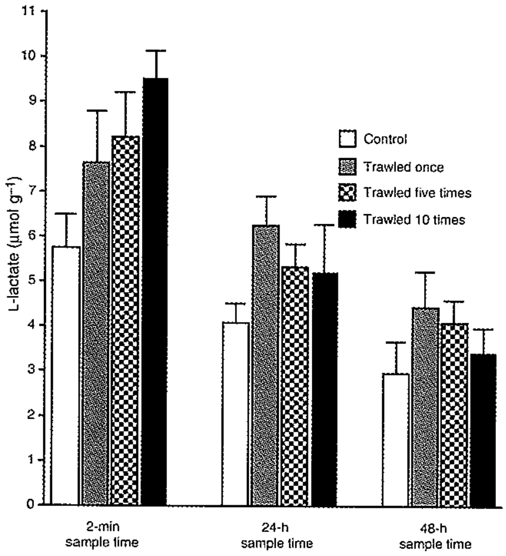

Fig. 4. Differences in mean L-lactate levels + 1 s.e. between the control and treatment prawns in Experiment 1 for each of the three sample times.

substratum. During the first rotation of the frame containing the 40-mm mesh panel and chain, prawns propelled themselves away and towards the second frame (containing the 40-mm and fine-meshed panels). Most individuals flicked back and forth at least two or three times, 'escaped' through the meshes in the first frame and then immediately burrowed into the sand. Similar behavioural responses to the frames were observed during the second successive rotation in the relevant treatments (i.e. five and 10 trawls), but by the third and fourth rotations, all prawns appeared to be exhausted and made no attempt to escape the path of the frame with the 40-mm mesh panel and chain or to bury themselves into the substratum (i.e. most individuals remained in the water column). It is apparent, therefore, that regardless of the level of repeated trawling, nearly all of the limited damage to prawns was done during the first rotation of the frame.

Analyses of the concentrations of L-lactate in the haemolymph of prawns in Experiment 1 support this conclusion, with ANOVA failing to detect any significant differences in mean levels for the main effect of the treatment of prawns (Table 2). A significant difference was detected among time for all prawns, with the highest mean levels (overall mean ± s.e. = 7.78 ± 0.5) recorded immediately after the aluminium frames were removed (i.e. at the 2-min sample time) (Fig. 4). These observed L-lactate concentrations are greater than those reported from the muscles of exercising yabbies, *Cherax destructor* (Phillips *et al.* 1977; Head and Baldwyn 1986), but similar to those recorded from anoxic prawns and crabs (although the latter can reach up to 15 or 20 μmol g^{-1}; Taylor and Spicer 1987; Hill *et al.* 1991).

Concentrations of L-lactate in all prawns were significantly reduced at 24 h (5.21 ± 0.36 μmol g^{-1}) and again at 48 h (3.72 ± 0.32 μmol g^{-1}), indicating a protracted recovery from stress. Although comparable observations have been made for other crustaceans (e.g. *Homarus gammarus*; Bridges and Brand 1980), most studies showed that tissue and/or haemolymph lactate levels in crustaceans returned to normal levels within approximately 12 h following anaerobiosis (e.g. Taylor and Spicer 1987; Spicer *et al.* 1990; Hill *et al.* 1991). One explanation for the results observed in the present study is that the levels of L-lactate at 48 h represent minimum baseline rather than routine levels of the metabolite in active school prawns. In support of this, Taylor and Spicer (1987) recorded levels of around 4 μmol g^{-1} wet weight in resting *Palaemon elegans* that were similar in size to the individuals examined here (sample weights of 0.84–1.98 g), while Paterson (1993) measured comparable levels in the muscles of chilled, immobilized penaeid prawns, before packing for export.

Although significantly more prawns died in treatment tanks (12.5%) than in control tanks (2.1%) after 14 days in Experiment 2, the overall post-multiple-trawl survival rate was >89%. It was not possible to examine the damage sustained by individuals that died during this experiment, as all were either partially or totally consumed by remaining prawns in the tanks. However, two of the four prawns that died during Experiment 1 showed substantial damage and in particular, breakages of the scaphocerites and chelete legs that were mostly distal to the plane of autontomy (Table 1). This damage was probably caused during contact with the 40-mm chain attached around the perimeter of the aluminium frame, and may have contributed to the mortality of some of the treatment prawns in Experiment 2. There were no significant differences between treatment and control tanks for the sizes and weights of individuals, so none of the treatment prawns that survived to the end of Experiment 2 were adversely affected in terms of their growth (Table 3).

Assuming that the results and their interpretations described in this laboratory study reflect what occurs in the field, we conclude that there are minimal deleterious impacts on juvenile school prawns as a result of multiple contact and escape through the meshes of prawn trawls. Simple increases in the mesh openings (to improve selectivity) can therefore be considered an appropriate means for reducing the fishing mortality of juveniles. However, it is important to remember that the results from the present study were limited to prawns encountering and escaping from simulated trawls. Other papers have described that many factors (e.g. differences in trawls, methods of operation, time spent in the trawl, the type and quantity of by-catch in the codend) can negatively affect the damage, stress and mortality of organisms escaping from trawls (e.g. Kaiser and Spencer 1995; Chopin *et al.* 1996). Future studies on the fate of post-trawled school prawns would benefit from an assessment of these effects.

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Atypical size selection of captive school prawns, *Metapenaeus macleayi*, by three recreational fishing gears in south-eastern Australia

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Abstract Three manipulative experiments were done to estimate the selectivity of conventional and new sizes and configurations of mesh for school prawns, *Metapenaeus macleayi*, in three south-eastern Australian recreational fishing gears (haul, push, and scoop nets). The treatment meshes examined were: (1) conventional-sized, diamond-shaped mesh used in all gears (20 mm in scoop nets and 30 mm in push and haul nets); (2) 30 mm in scoop nets; and (3) 40-mm diamond- and (4) 23-mm square-shaped mesh in all gears. In all experiments, known quantities of school prawns (6–24 mm carapace length (CL)) were placed in purpose-built enclosures, monitored to ensure no experimental-induced stress (as measured by changes in L-lactate in their haemolymph) and the replicate treatments of the various gear configurations deployed. Escapees from the various treatment nets were collected from the enclosures using fine-meshed nets. Logistic selection curves were derived for all treatment nets and specific comparisons made within and among gears. All nets had 50% retention lengths (L_{50}) comparable to other penaeid-catching gears with similar mesh sizes, but most had selection ranges (SRs) that were atypically inflated. The large SRs were attributed to a combination of factors that included the mesh geometry and towing speed of the gears and the behaviour of school prawns. The 20-mm scoop net had the smallest selection parameters, retaining >99% of individuals larger than 13 mm CL. Mesh size in this gear would need to be increased to at least 30 mm to allow some maturing prawns (>18 mm CL) to escape.

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INTRODUCTION

Recreational fishers target penaeids in many estuarine and nearshore areas throughout Australia (Ruello 1975; Kailola et al. 1993; Montgomery & Reid 1995). There is no information available on the total weight harvested, although a recent national recreational fishing survey estimated that 18.5 million individuals, comprising at least six species (Kailola et al. 1993), were caught throughout Australia during 2000/01 (Henry & Lyle 2003). Almost 60% of this catch included unspecified quantities of school *Metapenaeus macleayi*, eastern king *Penaeus plebejus*, and greasyback prawns *M. bennettae* retained during 251 000 fisher hours of effort in more than 120 estuaries along the New South Wales (NSW) coast (Henry & Lyle 2003).

The fishing gears legislated to catch these penaeids in NSW include hand-operated haul, push, and scoop nets; similar to those used in other Australian States (e.g., Kailola et al. 1993) and in the majority of the world's artisanal penaeid fisheries (e.g., Unar & Naamin 1979; George et al. 1981; Vendeville 1990; Sainsbury 1996). In NSW, these gears are managed by several input controls that include general restrictions on their: (1) methods of operation (e.g., continuous hauling or pushing); (2) maximum dimensions (e.g., 6-m headline for haul nets, 2.75-m footrope for push nets, and 0.6-m and 1.25-m hoop diameter and net length, respectively, for scoop nets); and (3) stretched mesh openings (30–36 mm for haul and scissor nets and 20 mm for scoop nets). Although there are few spatial and temporal restrictions on these gear-types, a 3-year creel survey of four coastal lagoons and estuaries by Montgomery & Reid (1995) revealed that scoop nets were the most popular (used by >93% of fishers at night using lights from boats or along the shore), followed by 30-mm haul (c. 6%) and push nets (<1%). The latter two gears typically are towed or pushed for between 1 and 10 min.

All these gears are used to target juvenile and subadult prawns (between 8 and 25-mm carapace length (CL); Henry & Lyle 2003; Montgomery & Reid 1995) throughout important nursery areas (Coles & Greenwood 1993), with estimated mean (±SE) catch per unit effort (by individual fishers) varying between 0.04 (±0.01) and 0.49 (±0.03) kg h^{-1} for scoop nets and between 0.05 (±0.03) and 0.94 (±0.0) kg h^{-1} for haul nets (Montgomery & Reid 1995). Although it is known that nearly all catches are retained (i.e., >97%—Henry & Lyle 2003) and that this probably impacts on the sustainability of stocks (Montgomery & Reid 1995), there are no formal estimates of the selectivity of the gears. This information is required to quantify the proportions of the different sizes harvested and to facilitate sustainable exploitation of stocks.

Three techniques are available for assessing the selectivity of these sorts of active gears (Pope et al. 1975; Wileman et al. 1996). The methods include using a particular treatment and fine-meshed control: (1) alternately (e.g., Broadhurst & Kennelly 1994); (2) simultaneously in a paired-gear configuration (e.g., Suuronen & Millar 1992); or (3) in a system where the fine-meshed net is rigged as a cover that retains escapees from the treatment gear (e.g., Sobrino et al. 2000). Providing the treatment and fine-meshed nets operate independently, the third configuration is usually preferred (Pope et al. 1975) because it provides direct observation of the population entering and escaping from the treatment net and ensures selection curves can be estimated for all replicate hauls (Wileman et al. 1996). Equally importantly, fewer replicates and smaller sample sizes will generally be required to provide meaningful selectivity estimates and comparisons among different gears.

A variation of the third technique (above) was used in the present study, but instead of attaching covers to the different recreational gears, they were tested under controlled conditions using relocated, wild-caught school prawns in enclosures specifically designed to retain all escapees. Unlike traditional cover-type experiments which assume no interactive effects (but see Macbeth et al. 2004), the methodology used here ensured independence between the cover and treatment nets. A concern with this approach, however, is the possible confounding effects of experimentally induced stress in school prawns, which could alter their activity and/or escape response. The potential for such effects can be determined by quantifying the concentrations of lactic acid in the haemolymph of experimental individuals and then comparing these to routine or base levels (Broadhurst et al. 2002).

Using the above controlled, manipulative experiment, our specific aims in the present study were to provide formal estimates of the size selectivity of school prawns by existing recreational gears used in NSW, and the effects of increasing lateral-mesh openings, via square- and larger diamond-shaped meshes.

MATERIALS AND METHODS

Three experiments were done at "Tru Blu" prawn farm, Palmers Island, NSW (29°26′S, 153°22′E) in May and June 2003 using a large earthen pond (100 × 100 × 1 m), five fibreglass (4 × 1000 litre and 1 × 3000 litre) and 35 smaller (70 litre) plastic holding tanks. All holding tanks were aerated and continuously supplied with water at a rate of c. 2 litre min^{-1}. Temperatures and salinities were c. 15 to 20°C and 17–18 psu, respectively.

Four rectangular-shaped enclosures were built into the earthen pond using steel pickets (2 m in length) buried 0.5 m apart to a depth of 0.5 m. The walls and floors of the enclosures were completely lined with panels of semi-rigid, black plastic (poly vinyl chloride (PVC)) 6-mm mesh (all mesh sizes refer to inside mesh opening) and sheeting (2 mm

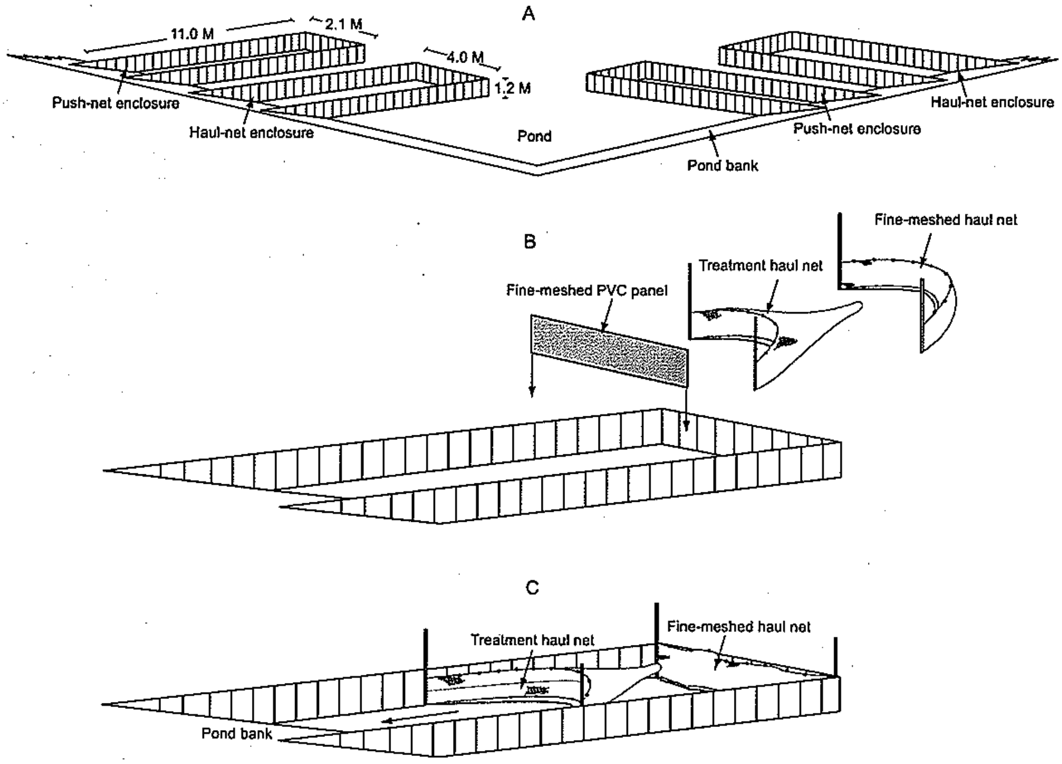

Fig. 1 Diagrammatic representation of **A**, earthen pond and enclosures; **B**, haul-net enclosure and positioning of the various panel and nets before towing; and **C**, towing the treatment net.

thick) (Fig. 1A). Enclosures were 11 and 1.2 m in length and height, respectively. Two of the enclosures were 2.1 m wide (termed the push-net enclosures), whereas the other two measured 4 m (termed the haul-net enclosures) (Fig. 1A). Each push- and haul-net enclosure was located parallel and adjacent to the other pair in one corner of the pond (Fig. 1A). Panels were made from fine-meshed PVC and designed to fit between the sides of the enclosures, dividing them into two separate compartments (Fig. 1B).

Collection of prawns

The three experiments were done consecutively, each over 4 days. On the first morning of each experiment, c. 10 000 school prawns (6–24 mm CL or 0.18–10.51 g) were captured in the Clarence River (5 km from the prawn farm) using twin trawls (40 mm mesh) rigged with codends made from 10-mm knotless polyamide (PA) mesh, towed for less than 10 min in shallow water (between 5 and 12 m). At the end of each tow, live prawns were emptied from the codends directly into holding tanks onboard the vessel and supplied with oxygen. The prawns were transported by road and transferred (using buckets) into the five fibreglass holding tanks. Prawns were monitored for mortalities (dead individuals were removed) and left to acclimatise in these tanks for 48 h. On the third morning of each experiment, the water level in all holding tanks was lowered (to c. 500 litres) and ice added to reduce the temperature to 12°C (effectively anaesthetising the prawns). Approximately 6500 prawns were selected, removed and placed in groups of c. 180 into each of the 35 plastic 70-litre holding tanks. Because there was no evidence of sexual dimorphism in the morphology of these sizes of school prawns (see Results section and Broadhurst et al. 2002), individuals were placed in tanks irrespective of their sex. These prawns were left to acclimatise for 15 h. On the fourth morning of each experiment, at least three of the small holding tanks were designated as

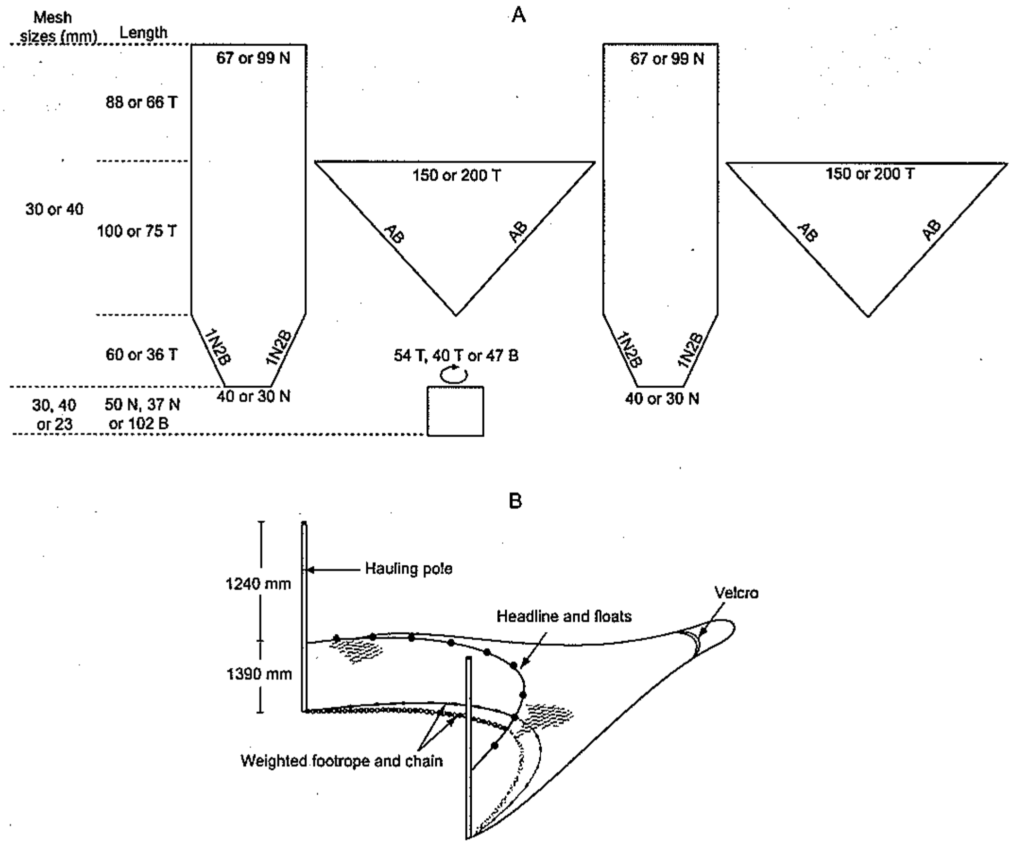

Fig. 2 **A**, treatment haul-net plans; and **B**, completed haul used in experiment 1. (N, normals; B, bars; T, transversals; AB, all bars.)

stock tanks and used to replace mortalities in the remaining tanks, which were subsequently used as replicates in the experiments described below. The numbers of prawns used in each of the replicates were within estimates of typical recreational catches for the various gears (Montgomery & Reid 1995).

Experiment 1: selectivity of haul nets

Four treatment (Fig. 2) and one fine-meshed haul net (Fig. 1B) were used in this experiment. All nets were constructed from white, knotted PA mesh (c. 0.4-mm diam., 3-strand twisted twine) hung at 50% on 6-m buoyed (9 × 57-mm floats) headlines and weighted (44 × 50 g leads) footropes. The footropes and headlines were attached to wooden poles at their base and a height of 1.39 m, respectively (Fig. 2B). A 5-m length of 5-mm chain link was attached between the bases of the wooden poles to: (1) ensure continuous contact of the haul nets with the bottom of the enclosure; and (2) help stimulate those school prawns orientated on the bottom to rise up into the net (Fig. 2B). All treatment haul nets were configured from two net bodies and three codends (Fig. 2A). The net bodies and two of the codends were made from 30- and 40-mm mesh (all mesh sizes refer to stretched mesh opening), respectively (Fig. 2A). The third codend was made from 23-mm mesh hung on the bar (i.e., square-shaped—with a bar length of 11.5 mm). The two net bodies and each of the three codends were rigged with velcro (0 56 m in length) to facilitate their attachment (Fig. 2B). The length of velcro was calculated assuming a fractional diamond-mesh opening of 0.35 × the mesh size × the number of meshes in circumference. The four treatment haul-net configurations examined included the 30-mm haul body attached to (1) the 30-mm codend (termed the 30-mm haul) and (2) the 23-mm square-mesh codend (termed the 30-mm/square haul), and the 40-mm haul body attached to (3) the 40-mm codend (termed the 40-mm haul) and (4) the 23-mm square-mesh codend (termed the 40-mm/ square haul). The fine-meshed haul net was made from a rectangular piece of 9-mm mesh (measuring 400 normal meshes (N) × 108 000 transversal meshes (T)) (Fig. 1B).

The treatment haul-net configurations were alternately tested in the two haul-net enclosures. The procedure involved inserting the fine-meshed PVC panel, treatment being tested and fine-meshed haul net c. 2 m from the end of the enclosure (Fig. 1B). A 70-litre holding tank containing c. 180 prawns was randomly selected and emptied into the enclosure between the fine-meshed PVC panel and the pond bank. Prawns were left to disperse into the forward section of the enclosure for 1 min, after which the fine-meshed screen was removed and the treatment haul immediately dragged (by two people) at c. 0.15 ms^{-1} along the enclosure and out onto the pond bank (Fig. 1C). The towing speed and haul duration were within estimates for typical recreational fisheries. All of the treatment haul nets maintained continuous contact with the sides and bottom of the enclosures, ensuring that prawns had to enter the nets and either escape through the meshes or be retained. Immediately after each treatment haul net was removed, the fine-meshed haul net was immediately towed through the enclosure (to capture all of the prawns that had escaped). Two subsequent tows of the fine-meshed haul net were done to confirm that no escapees remained in the enclosures. The position and order of the treatment haul nets was determined randomly and, between 0700 and 2000 h on the fourth day of the experiment, we completed four replicate deployments of each treatment in each of the two enclosures (i.e., a total of 8 replicate tows per treatment).

Experiment 2: selectivity of push nets

Three treatment push nets and the fine-meshed haul net were used in this experiment. The push nets were made from the same mesh sizes, orientations, and hanging ratios as those used in experiment 1 and were termed the 30- and 40-mm (Fig. 3A) and 23-mm square push nets (Fig. 3B). An aluminium frame (termed the scissors frame) was designed so that the push nets could be interchanged (Fig. 3C). The scissors frame also included two PVC mesh (6 mm) panels designed to prevent prawns escaping over either of the apex and to direct them into the net (Fig. 3D). Using the same methodology as that described for experiment 1, on the fourth day of the experiment (between 0700 and 1500 h) the treatment push nets (and the fine-meshed haul net) were randomly and alternately deployed 4 times in each push-net enclosure.

Experiment 3: selectivity of scoop nets

Four treatment scoop nets were examined. Three of the scoop nets were made from the same sizes and orientations of mesh described above, whereas the fourth was constructed from 20-mm diamond-shaped mesh (i.e., conventional-sized mesh) (Fig. 4A). Each of the scoop nets was secured (at a hanging ratio of 80%—as per recreational practice) to a frame measuring 1.7 m in circumference (Fig. 4B). A cover, made from 6-mm PVC mesh, was designed to entirely enclose the scoop nets and retain any escaping prawns (Fig. 4C). The experimental procedure involved positioning the particular treatment scoop net being tested and the cover assembly in the 3000 litre holding tank and slowly pouring (over 10–15 s) the prawns (i.e., c. 180) from a randomly-selected 70-litre holding tank into the scoop. After 10 s, the scoop net was lifted out and then returned to the water three times before being removed from the tank. The aim of this procedure was to simulate multiple insertions, as per recreational fishing practice. Scoop net deployment was randomised and we completed 8 replicates of each treatment between 0700 and 1200 h on the fourth day of the experiment.

Data collected

To monitor the relative stress levels of prawns, six individuals were randomly-selected at three sample periods during each experiment: (1) 48 h after being placed in the large fibreglass holding tanks (on day 3, immediately before being transferred to the 70-litre holding tanks); (2) 15 h after being placed in the 70-litre holding tanks (on day 4, immediately before starting the replicate gear deployments); and (3) immediately after the fine-meshed haul or cover net corresponding to the fifth deployment of the treatment gear was removed from the pond enclosures or tank (on day 4). The six prawns were immediately secured in labelled aluminium satchels and frozen in liquid nitrogen. Analyses of L-lactate were done for four frozen prawns (and not six—because of the cost involved) at each period following the methods described by Broadhurst et al. (2002).

The CLs, maximum heights (MH) and widths (MW) to the nearest 0.1 mm were recorded for 100 randomly-selected males and females. All other prawns caught in the replicate deployments of the

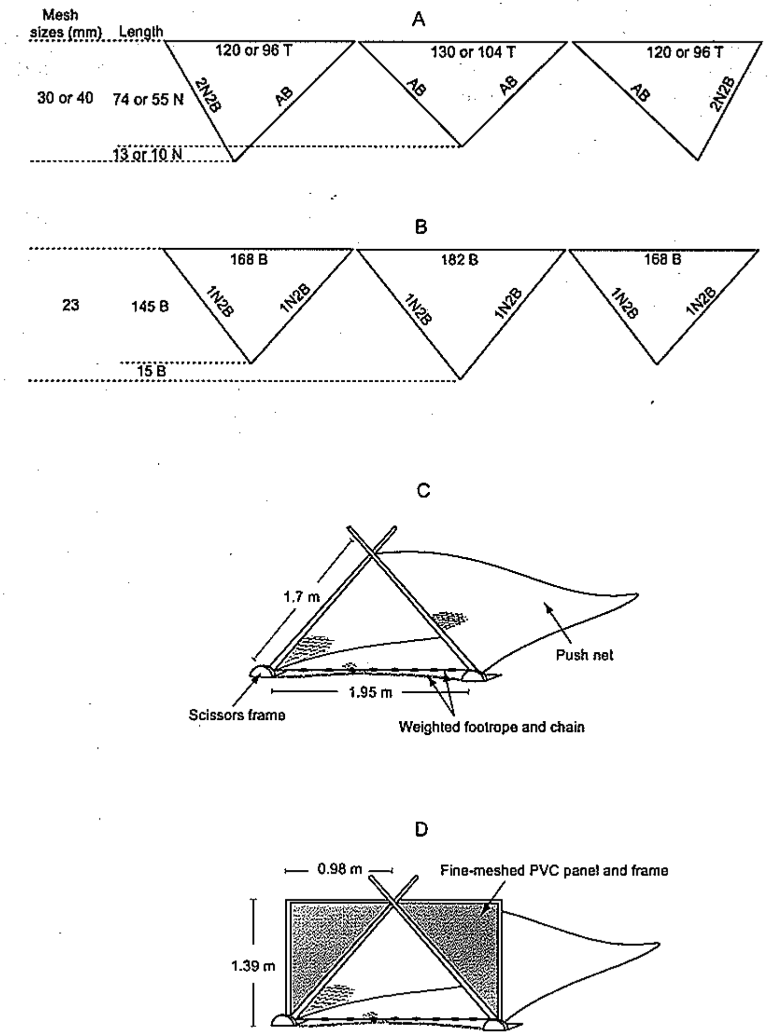

Fig. 3 **A**, 30- and 40-mm and **B**, 23-mm square push-net plans; **C**, scissors frame with push net attached; and **D**, completed scissors frame with fine-meshed PVC panels attached used in experiment 2. (N, normals; B, bars; T, transversals; AB, all bars.)

various treatment nets and their controls/covers were measured to the nearest 1-mm CL.

Statistical analyses

The concentrations of L-lactate (μmol g^{-1}) from the four randomly-selected prawns at the three sample times in each experiment were tested for heteroce-dasticity using Cochran's test and then analysed using orthogonal two-factor analyses of variance (ANOVA). In these analyses, the experiment and time of sampling were considered fixed and random factors, respectively.

Linear regressions of MH and MW against CL were fitted separately for male and female school prawns and compared using appropriate analyses of co-variance (ANCOVA). These analyses failed to detect any significant sexual dimorphism in morphology (see Results section) and so the selectivity models for the various treatment gears described below were done irrespective of sex.

All selection curves were fitted using individual haul data that were "stacked" within each gear type (Millar et al. 2003). For example, if each of eight deployments counted 20 length classes, then the stacked individual haul data would comprise 160 catch records. This procedure provides precisely the same selection curve obtained by summing the data over all deployments, but allows between-haul

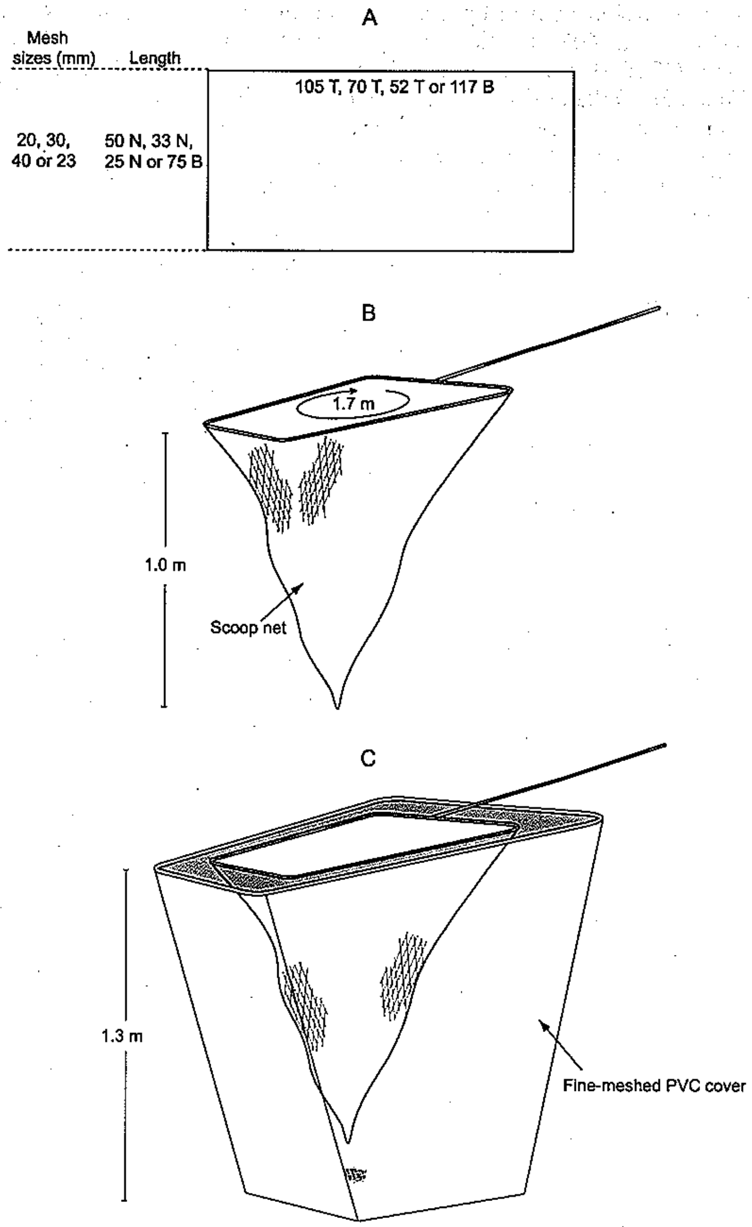

Fig. 4 **A**, scoop-net plans; **B**, scoop net and frame; and **C**, scoop net and fine-meshed panel assembly used in experiment 3. (N, normals; B, bars; T, transversals; AB, all bars.)

variation to be gauged. Moreover, the stacked data can be used in mixed-effects modelling of between-haul variation (Millar et al. 2003) using the PROC NLMIXED procedure in SAS. We first tested for any significant effects of the enclosures for the haul and push net replicate deployments (4 replicates in each enclosure). This was done using mixed-effects modelling with the fixed effects being the difference in length of 50% retention (L_{50}), and selection range (SR) between enclosures. The random effects were between-haul variation in L_{50} and SR (see Appendix A of Millar et al. 2003). No significant effects of enclosures were detected and so, like the scoop net data, the haul net and push net data were stacked over all eight replicate deployments.

Individual logistic and Richard's selection curves were obtained from maximum likelihood fits to the stacked individual haul data, with REP correction for overdispersion arising from between-haul variation (Millar et al. 2003). The fits were implemented using both CC2000 (www.constat.dk) and ccfit (an R function available from www.stat.auckland.ac.nz/~millar/selectware/code.html). Alternatively, selection curves could have been obtained using mixed-effects modelling, but the REP correction approach was used for ease of interpretability. The estimated selection curves can be interpreted as unbiased estimates of the fishery-wide selectivity of these gears, provided that the experimental deployments were typical of deployment in the recreational fishery. Likelihood ratio tests were used to test for differences between the selection curves (1) within gear types for the different sizes and configurations of mesh and among (2) all gear types for the 30- and 40-mm mesh and (3) the push and scoop nets for the 23-mm mesh hung on the bar.

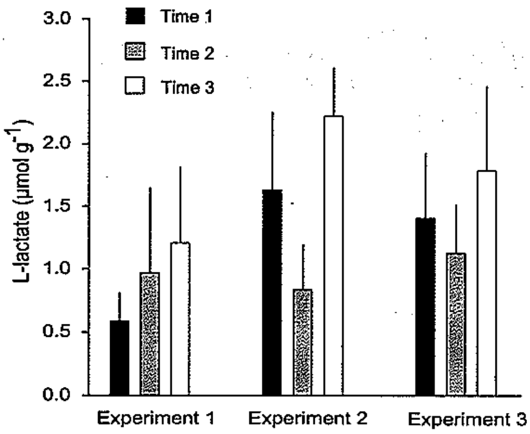

Fig. 5 Differences in mean L-lactate levels (+ SE) between the three experiments for each of the three sample times.

RESULTS

Prawns used in experiments

Approximately 9000 of the total 30 000 prawns caught and placed in the various holding tanks died during the three experiments. Most mortalities occurred in the large holding tanks and within 24 h of capture. It was not possible to obtain accurate estimates of mortalities during this period because many dead prawns were quickly consumed (precluding their counts) by the remaining prawns in the various tanks.

ANOVA on the L-lactate concentrations of prawns failed to detect significant effects of experiment (F-ratio = 2.98, $P > 0.05$) and time sampled (F-ratio = 1.72, $P > 0.05$) or an interaction (F-ratio = 0.44, $P > 0.05$). Mean L-lactate concentrations (± SE) ranged between 0.5 ± 0.21 and 2.22 ± 0.38 μmol g^{-1} (Fig. 5) and approached baseline levels (3.72 ± 0.38 μmol g^{-1}) previously recorded for this species (e.g., Broadhurst et al. 2002). Such low levels of the metabolite in active school prawns indicate that they were not overly stressed during the experimental procedure.

The relationships between CL and MH and MW revealed that many of prawns used in the experiments had morphological dimensions that were less than the maximum diagonal and lateral openings of the smallest mesh size examined (i.e., 14.1 mm for the 20-mm mesh) and that all prawns could have passed through the 23-mm mesh hung on the bar (Fig. 6). This result was independent of sex because ANCOVA failed to detect significant differences in

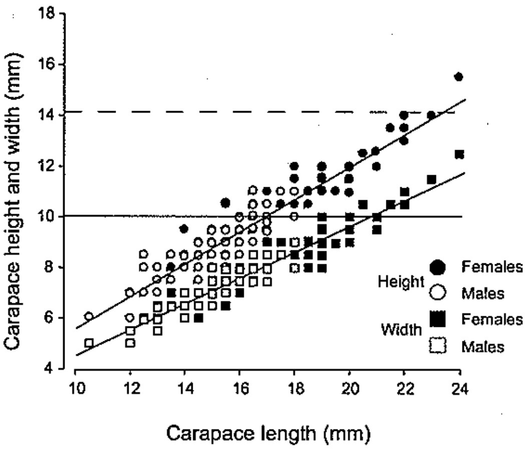

Fig. 6 Common linear regressions between the carapace length and maximum height and width for school prawns measured in the study (n = 200). Solid and dashed horizontal lines represent the maximum diagonal and lateral openings of the smallest mesh size (20 mm) examined, respectively.

slopes or elevations between the regressions ($P > 0.05$) for males (MH = 0.646CL–0.947, $r^2 = 0.78$, MW = 0.533CL–0.824, $r^2 = 0.84$) and females (MH = 0.608CL–1.69, $r^2 = 0.88$, MW = 0.508CL–0.467, $r^2 = 0.89$). Common regressions were calculated as MH = 0.638CL–0.766 and MW = 0.511CL–0.496 (Fig. 6).

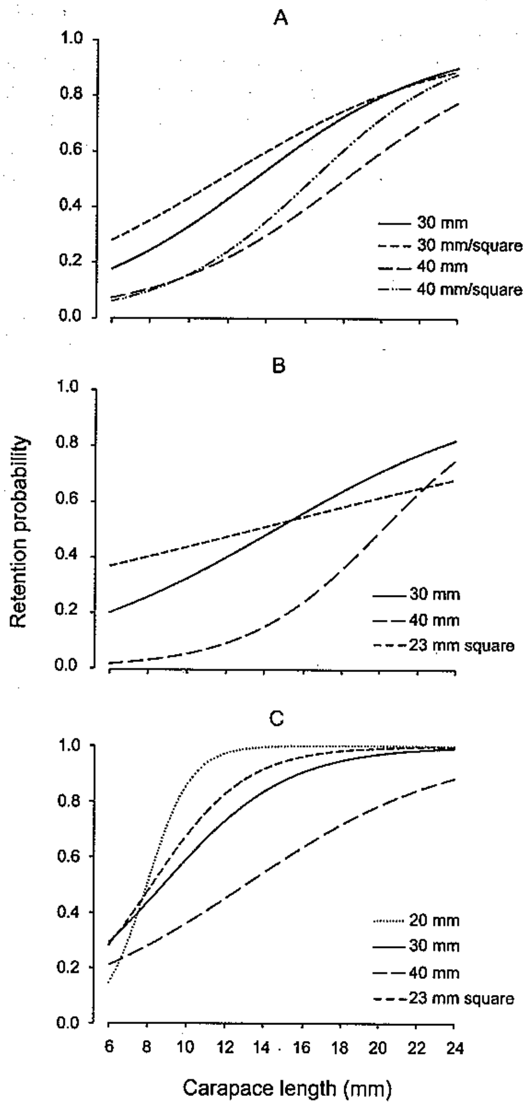

Fig. 7 Logistic selection curves for school prawns from the various treatment **A**, haul; **B**, push; and **C**, scoop nets tested in this study.

Selectivity of gears

Using likelihood ratio tests and examination of deviance residuals, logistic selection curves were found to provide the most parsimonious fit and were used throughout. The estimated selection curves and parameter vectors (L_{50} and SR) from the stacked-data fits are presented in Fig. 7 and Table 1, respectively. Although the L_{50}s (Table 1) for the three smallest scoop net configurations were close to the minimum sizes of school prawns used in the experiment (i.e., 6 mm), and therefore should be treated with some caution, the configurations were nevertheless almost non-selective for the size range of individuals typically encountered by recreational fishers (Montgomery & Reid 1995; Henry & Lyle 2003). With the exception of the 20-mm scoop net, all gear configurations were characterised by wide SRs. Likelihood ratio tests detected significant differences between all comparisons within gear types ($P < 0.05$), except between the 40-mm and 40-mm/square haul nets ($P > 0.05$). Similarly, the comparisons of relevant mesh sizes between gears resulted in highly significant differences ($P < 0.01$) for all combinations, except between the 30-mm haul and push nets ($P > 0.05$).

DISCUSSION

All of the mesh sizes used in the three gears tested during this study selected school prawns at L_{50}s that were comparable or larger than those recorded from towed commercial gears using similar-sized mesh to target this species in NSW (Broadhurst et al. 2004a) and other penaeids elsewhere (Vendeville 1990; Sobrino et al. 2000). However, unlike most penaeid-catching gears, all of the configurations examined here, except for the smaller-meshed scoop nets, partially retained individuals across the entire range

Table 1 Carapace lengths (mm) at 50% probability of retention (L_{50}) and selection ranges (SR) for school prawns *Metapenaeus macleayi* from the various fishing gears and their sizes and orientations of mesh. Standard errors are given in parentheses.

	L_{50}	SR
Haul nets		
30 mm	13.42 (0.35)	10.52 (1.39)
30 mm/square	11.65 (0.52)	12.97 (2.01)
40 mm	18.11 (0.66)	10.44 (1.46)
40 mm/square	16.42 (0.44)	8.36 (1.13)
Push nets		
30 mm	14.58 (0.39)	13.63 (2.18)
40 mm	20.15 (0.66)	7.73 (0.93)
23 mm square	13.50 (0.94)	30.68 (11.19)
Scoop nets		
20 mm	7.99 (0.40)	2.47 (0.26)
30 mm	8.83 (0.86)	7.03 (0.98)
40 mm	13.07 (0.67)	11.77 (2.38)
23 mm square	8.25 (0.79)	5.26 (0.70)

of sizes sampled (i.e., between 6 and 24 mm CL). This corresponded to low-sloping selection curves with relatively high estimated SRs (Fig. 7, Table 1). In the most extreme example, and although estimated with poor precision, the 23-mm square push net had an SR that was more than double its L_{50} (Table 1).

Such inflated, atypical SRs can be attributed to the influences of a combination of factors that included: the (1) mesh geometry in the various gears; (2) towing or hauling speed; and (3) morphology and behaviour of school prawns. All of the treatment mesh sizes, except for the 20 mm used in the scoop net, had diagonal and lateral openings that were wider than the maximum cross-sections of the largest school prawns sampled (Fig. 6). Although prawn-catching gears are constructed using similarly-proportioned mesh sizes (e.g., Vendeville 1990; Broadhurst et al. 2000, 2003a; Sobrino et al. 2000), variables such as the volume of netting attached to the fishing line (i.e., the hanging ratio), thickness of twine, angle of body taper, towing speed, and weight of catch in the codend ensures that meshes open at a fraction of their overall size (Reeves et al. 1992; Lowry & Robertson 1996; Lök et al. 1997; Broadhurst et al. 2000). For example, underwater observations of codends and extension sections in demersal trawls have revealed lateral mesh openings typically between 0.15 and 0.25 of the stretched mesh length (Robertson 1986). In contrast to these gears, all of the recreational nets examined here had a light construction (e.g., 0.4-mm ø twine), low volume of netting, and were slowly towed or hauled (i.e., at 0.15 ms^{-1}) through the water. These characteristics, combined with the steep body tapers (c. 45°), means that most lateral mesh openings were maximised (regardless of their diamond or square orientation) and that prawns had a high probability of contacting meshes during fishing. Since varying proportions of relatively small and large school prawns were nevertheless retained in most gears, selection was strongly influenced by variables other than size; which probably included the behaviour and random orientation of individuals during their capture. In support of this, we observed that some school prawns quickly contacted the sides and tops of the nets with their anterior carapace and then immediately passed through the open meshes, or made subsequent attempts at escape. Conversely, other individuals that were orientated laterally to the mesh either became entangled, or swam in the direction of the tow and were progressively herded towards the codend (or bag). Some school prawns were observed to escape at this section, although many were entangled in the meshes and subsequently retained.

These observations indicate that selection occurred at all sections of the gears and are supported by the differences in parameters between the various haul-net configurations. For example, the haul nets made entirely of 30- and 40-mm mesh selected school prawns across similarly wide SRs at L_{50}s of 13.42 and 18.11 mm, respectively. Replacing the 30- and 40-mm diamond-mesh codends in these gears with the same 23-mm square-mesh codend maintained comparable SRs, but reduced the L_{50}s of the entire gears by similar amounts to 11.65 and 16.42 mm CLs, respectively. These slight (and non-significant for the 40-mm haul) reductions in L_{50} can be explained by some consistent influence of the codend on overall selectivity. But the remaining observed and highly significant differences between the 30- and 40-mm gears were a result of selection throughout their net bodies. Previous studies support the potential for selection in the wings and bodies of towed gears (High et al. 1969; Vendeville 1990), although few attempts have been made to quantify the effects of altering meshes in these sections (but see Broadhurst et al. 2000; Polet 2000). Our observations suggest that future studies on similar towed nets could benefit from some assessment of the selectivity of the entire gear and not just codends.

There are no minimum legal sizes for any of the penaeid species caught in NSW and so recreational fishers target and retain virtually all catches (Montgomery & Reid 1995). Estimates of the size at maturity for the key species are between 34 and 42 mm CL for eastern king prawns (Glaister 1983; Courtney et al. 1995) and >16 and 18 mm for greasyback (Dall 1958) and school prawns (Glaister 1978), respectively. Assuming minimal inter-specific differences in selection parameters among these species (Broadhurst et al. 2004a,b; Macbeth et al. 2004), the results presented here indicate that, although some mature penaeids probably escape from the conventionally-used 30-mm haul and push nets (i.e., 28 and 37% of school prawns at 18-mm CL), few (if any) escape from the 20-mm scoop net. This latter gear retained >99% of all school prawns larger than 13 mm CL. Increasing the mesh size to 30 mm would significantly improve the probability of some maturing school prawns escaping from scoop nets (Fig. 7, Table 1). Owing to their popularity (e.g., used by >93% of operators—Reid & Montgomery 2004), any increase in the mesh size of scoop nets could substantially reduce the fishing mortality of juvenile penaeids—providing the majority of escapees survive.

Although the fate of school prawns escaping from recreational gears was not examined here, a previous study by Broadhurst et al. (2002) demonstrated minimal stress, physical damage and mortality (<11% over 2 weeks post-escape) by the same size cohort after their simulated multiple capture and escape from trawls. During this earlier work, the mean L-lactate concentration recorded from school prawns at 2 min post-escape (7.78 ± 0.5 µmol g^{-1}) was considerably greater than that observed here (e.g., between 0.58 ± 0.22 and 1.63 ± 0.61 µmol g^{-1}—Fig. 5). This result supports the hypothesis that the capture and escape of school prawns from recreational gears has minimal effect on their condition.

Although this study has quantified the selectivity of different recreational gears used in NSW, it is important to consider that the parameter estimates are only valid for the configurations tested. It is well-established that several inter-related factors influence the selectivity of towed fishing gears, independent of the size of mesh used (e.g., Reeves et al. 1992; Lowry & Robertson 1996; Broadhurst et al. 2000). As with all gears, therefore, any alterations to the designs of recreational nets examined during this study (e.g., different hanging ratios, twine material and thickness, etc) will probably influence their selectivity.

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Selectivity of conventional diamond- and novel square-mesh codends in an Australian estuarine penaeid-trawl fishery

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Abstract

The selectivities and relative efficiencies of (i) two conventional diamond-mesh codends with posterior sections 100 and 200 meshes in circumference and (ii) two novel square-mesh codends with different circumferences throughout and comprising panels of square-shaped mesh instead of drawn-strings were investigated in a New South Wales estuarine penaeid-trawl fishery. Paired simultaneous comparisons (using twin trawls) of each of these four treatment codends with their respective small-meshed controls showed that the conventional diamond-mesh codend with a 200 mesh posterior circumference had no detectable selectivity for all sizes of the school prawns, *Metapenaeus macleayi* and eastern king prawns, *Penaeus plebejus* encountered. While reducing the posterior circumference to 100 meshes marginally improved selectivity, both of the novel square-mesh codends were the most effective designs in selecting significantly larger prawns across a smaller range of sizes and releasing up to 99% more fish than the conventional diamond-mesh codend with the 200 mesh posterior circumference. The results are discussed in terms of the influences of the geometry of the various codends on their performances and the importance of examining simple changes to codend meshes as a means for augmenting bycatch reduction from penaeid prawn trawls.

Keywords: Selectivity; Shrimp; Gear technology; Square-mesh codends; Bycatch reduction

1. Introduction

In New South Wales (NSW), Australia, estuarine otter trawling occurs at four locations, involves up to 247 small vessels (<10 m in length) and is valued at approx. A$ 7 million per annum. Fishers target penaeids and mostly school prawns, *Metapenaeus macleayi*, but also catch and discard a diverse assemblage of unwanted small fish, cephalopods and crustaceans (collectively termed bycatch) (Liggins and Kennelly, 1996; Liggins et al., 1996). Concerns over the mortality of large numbers of juveniles of commercially important species of fish led to the development of physical modifications to trawls (for a review see Broadhurst, 2000) designed to reduce bycatch. This culminated in the adoption and legislation of several bycatch reduction devices (BRDs), including the Nordmøre-grid, which was designed to

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partition the catch mechanically and to exclude all individuals larger than the targeted prawns. This BRD was shown to be effective in reducing up to 90% of bycatch, with no significant effects on the catches of prawns (Broadhurst and Kennelly, 1996a).

The Nordmøre-grid has alleviated concerns over the potential impacts of trawling on many of the species comprising bycatch in NSW's estuarine prawn-trawl fisheries. An issue that still remains, however, concerns the unwanted capture of organisms smaller than the targeted school prawns (i.e. individuals not excluded by the Nordmøre-grid) and, in particular, conspecifics considered to be too small for sale. While there is no minimum legal size for school prawns in NSW, operators in most fisheries conform to industry-recommended 'counts' which vary from approx. 150–180 prawns 500 g^{-1} (i.e. mean individual weights of 3.3–2.7 g or mean carapace lengths, CL, of approx. 17–15 mm, respectively). There have been no formal estimates of the selectivity of the minimum legal mesh size (40 mm inside mesh opening) used in commercial trawls, but it is apparent that large numbers of prawns considerably smaller than the above optimal size are caught (Broadhurst and Kennelly, 1996a) and then discarded dead. This is considered a major waste of stocks because if these individuals were able to escape through trawl meshes, many would survive (Broadhurst et al., 2002b) and reach commercial size within a few months (Glaister, 1978).

The retention of juvenile school prawns and other very small individuals comprising bycatch is due to the materials and rigging arrangements of conventional diamond-mesh trawls. Like many penaeid-trawl fisheries throughout the world, those in NSW use codends with large posterior circumferences (e.g. hanging ratios of up to 0.5) and knotted mesh made from thick twine (Vendeville, 1990; Broadhurst and Kennelly, 1996b). This substantially reduces the lateral openings of the meshes in the codend and the overall trawl selectivity (Reeves et al., 1992; Broadhurst and Kennelly, 1996b; Lowery and Robertson, 1996; Lök et al., 1997).

Some of the simplest ways to increase selectivity, therefore, are to reduce the fishing circumference of the codend (i.e. increase the hanging ratio) and/or open meshes by orientating them on the bar so that they are square shaped. These sorts of modifications have successfully been applied in many fish- and crustacean-trawl fisheries (e.g. Suuronen and Millar, 1992; Thorsteinsson, 1992; Lök et al., 1997; Stergiou, 1999) and more recently in an Australian penaeid-trawl fishery (Broadhurst et al., 1999b, 2000). For example, in Gulf St. Vincent, Broadhurst et al. (1999b) showed that compared to a conventional diamond-mesh codend, those made entirely with square meshes and comprising narrow circumferences significantly reduced the bycatch of small fish and unwanted juvenile western king prawns, *Penaeus latisulcatus* with no concomitant loss of commercial catch. The improved selectivity for the target-sized western king prawns was attributed to a greater probability of small individuals encountering openings in the narrow square-mesh codends and escaping.

One problem with the codends examined during this work, however, was a reported variability in performance during extreme catches. Because the meshes were square shaped and codend circumference was narrow, large catches could not expand laterally and often became wedged in the posterior section of the codend, making it difficult to remove when the codend was retrieved and the draw-strings were opened. Conversely, during hauls with very small catches, square meshes have been observed to convolute over a large proportion of the posterior section of the codend (Robertson, 1986) reducing the number of mesh openings and therefore the selectivity.

We addressed the potential for the above effects in the present study by designing a new square-mesh codend that included a circular panel of square-shaped mesh instead of the traditional draw-string and laterally located zippers to release the catch through the sides of the codend. Our specific objectives in this work were to quantify the selectivities and efficiencies of two of these new square-mesh designs (made from 20 mm mesh hung on the bar and with different circumferences) and two conventional diamond-mesh codends (with posterior sections hung at ratios of 1.0 and 0.5, respectively) for catches and bycatches in a typical NSW estuarine penaeid-trawl fishery.

2. Materials and methods

This study was done on commercial prawn-trawl grounds in Lake Woolooweyah (part of the Clarence River estuary in NSW: 29°26′S, 153°22′E) in March

2002 using a chartered commercial prawn trawler (10 m in length). Two Florida Flyer trawls each with a headline length of 7.32 m were rigged in a standard twin-gear configuration (one on each side of the vessel) and towed at $1.2\,m\,s^{-1}$ over a combination of sandy and mud bottoms in depths ranging from 1 to 3 m. Both trawls contained aluminium Nordmøre-grids with bar spaces of 20 mm (for details on rigging see Broadhurst and Kennelly, 1996a). Zippers (Buraschi S146R, 1.45 m in length) were attached immediately posterior to the Nordmøre-grids to facilitate changing of the codends. The length of these zippers was based on the expected fishing circumference of the anterior section of a conventional diamond-mesh codend and calculated assuming a fractional mesh opening (Broadhurst et al., 1999b) of 0.35 × the circumference in number of meshes × the stretched mesh length (see Ferro and Xu (1996) for definitions of mesh size).

2.1. Codends examined

Six codends were constructed: two conventional diamond-mesh designs, two square-mesh designs and two appropriate controls (i.e. made from diamond- and square-shaped mesh, respectively, with mesh sizes approx. ≤50% of the treatment codends (Wileman et al., 1996). All codends were made from dark netting and had a total length and maximum anterior fishing circumference of approx. 2.40 and 1.45 m, respectively. The first and second codends, termed the 200 and 100 diamond codends, represented conventional designs and were made entirely of 40 mm (unless stated otherwise, all mesh sizes refer to diamond mesh opening, see Ferro and Xu (1996) for definitions) knotted polyethylene mesh netting (≤3 mm diameter twisted and braided twine) (Fig. 1A and B). Both codends had identical anterior sections that were 33 meshes in length and 100 meshes in circumference (Fig. 1A and B). Their posterior sections were both 25 meshes in length but had circumferences of 200 and 100 meshes, respectively (Fig. 1A and B). The third codend, termed the diamond control, was made from 20 mm knotless polyamide netting (2.5 mm diameter braided twine) and had a circumference of 200 meshes throughout (i.e. an approximate fishing circumference of 1.45 m) (Fig. 1C). All three diamond-mesh codends were rigged with conventional draw-strings to close their posterior sections.

The fourth and fifth codends, termed the non-tapered and tapered square codends, were made entirely from 20 mm knotless polyamide netting (2.5 mm diameter braided twine) that was hung on the bar (i.e. the meshes were orientated so that they were square shaped) (Fig. 1D and E). The non-tapered square-mesh codend had a circumference of 110 bars throughout (Fig. 1D), while the tapered square-mesh codend had a circumference of 110 bars at the start of the anterior section that was reduced to 54 bars at the end of the posterior section (i.e. a 50% reduction in fishing circumference) (Fig. 1E). It was hypothesised that this taper would increase the probability of prawns encountering open meshes and therefore the selectivity of the codend (see Section 1). The sixth codend, termed the square control, was made entirely from 6 mm (mesh opening or 7 mm mesh length) knotless polyamide netting (1.5 mm diameter braided twine) hung on the bar and without a taper (Fig. 1F). To maintain symmetry, all three square-mesh codends were constructed in two sections; each section comprising upper and lower panels sewn together with opposite knot directions (see also Broadhurst et al. (1999b) for construction details) (Fig. 2). Appropriate-sized circular panels of square-shaped mesh were attached to the ends of the posterior sections of the three square-mesh codends and, instead of a conventional draw-string, zippers (Buraschi S146R, 0.3 m in length) were attached to each of the lateral seams to allow removal of the catch (Fig. 2). It was thought that this would improve selectivity by maintaining codend geometry and mesh openings.

2.2. Experimental procedure

The four treatment codends were compared against their respective controls in independent, paired hauls. In each paired comparison, the particular treatment and control codend being tested were attached posterior to the Nordmøre-grids (Fig. 2) in the twin-rigged trawls and towed simultaneously. The position and order of each codend was determined randomly and they were used in normal commercial hauls of 30 min duration between 0700 and 1400 h each day. Two replicate tows of each test codend against its control were done on each day, providing a total of 20 replicate hauls for each comparison over 10 days.

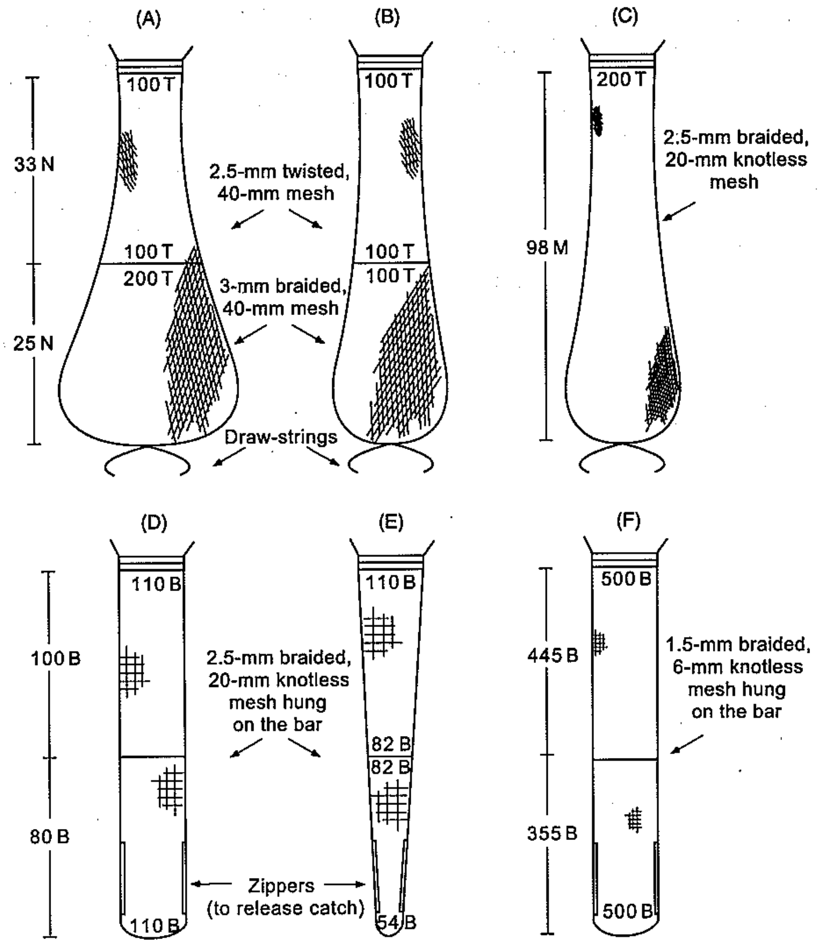

Fig. 1. Schematic diagram of (A) 200 diamond, (B) 100 diamond, (C) diamond control, (D) non-tapered square, (E) tapered square and (F) square control codends. N, normals; T, transversals; B, bars.

After each tow, the two codends being tested were emptied onto a partitioned tray. Prawns and all individuals of commercially important species comprising bycatch were separated by species. Following removal of a subsample (see below), school prawns were further separated (by the skipper of the vessel) into either commercially retained or discarded categories. The following categories of data were collected for each tow: the weight of total prawns; the weight of total school prawns and a subsample (250 prawns from each codend) of their lengths (to the nearest 1 mm CL); the number of total school prawns (estimated from the subsample); the percentage (by weight) of discarded school prawns; the total weight, number and sizes of eastern king prawns, *Penaeus plebejus*; the weight of total bycatch; the number of all commercially important species comprising bycatch and the sizes of commercially important fish; and the numbers of non-commercial species. Approximately 500 school prawns were collected from several randomly selected hauls during the experiment and 110 eastern king prawns collected after the experiment was completed. These individuals were separated by sex and then weighed and measured in the laboratory

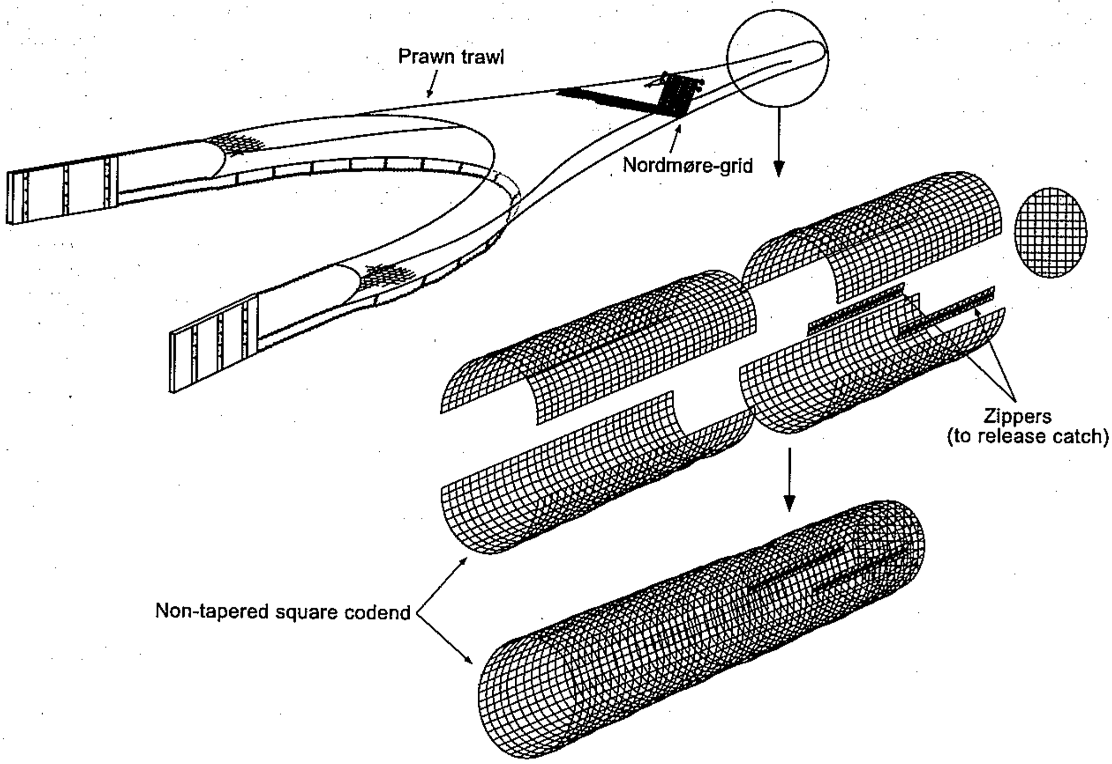

Fig. 2. The location of the Nordmøre-grid in a prawn trawl and the panel assembly for the square-mesh codends.

to the nearest 0.1 g and 0.1 mm CL, respectively. These latter samples and measurements were taken to facilitate accurate determination of length/weight relationships for school and eastern king prawns.

2.3. Statistical analyses

An orthogonal, two-factor analyses of variance (ANOVA) model was used to test the hypotheses of no differences in catches between the four treatment codends. In these analyses, codend type and days were considered fixed and random factors, respectively. The effect of days was considered multiplicative and so catch data for replicate hauls that had sufficient numbers of each variable (i.e. at least 1 individual in at least 10 replicates) were $\ln(x + 1)$ transformed. All transformed data were tested for heterocedasticity using Cochran's test and then analysed by ANOVA. To increase power for the main effect of codend type, where the interaction term was non-significant at $P < 0.25$, it was pooled with the residual (Winer, 1971). Significant differences detected in these analyses were investigated using Student–Newman–Keuls (SNK) multiple comparisons.

Linear regressions of log wt (g) against log CL (mm) were fitted separately for male and female school and eastern king prawns and then compared intraspecifically using appropriate analysis of covariance (ANCOVA). These analyses failed to detect significant intraspecific dimorphism in the weight/length relationships across the range of sizes examined (see Section 3). The selectivity estimates for the various treatment codends described below were therefore done irrespective of sex.

Size-frequencies of individuals of species caught in sufficient quantities were combined across all tows and logistic and Richards selection curves fitted to these data using maximum likelihood. These fits used the estimated-split SELECT model for trouser trawls (Millar and Walsh, 1992) and were implemented using the free software package R and selectivity functions downloaded from http://www.scitec.auckland.ac.nz/~greebie/selectware/R. Model fits were assessed by visual examination of deviance residuals and by comparing model deviances and associated degrees of freedom with a chi-squared distribution (Millar and Fryer, 1999). When the individual tows had sufficient data, model deviances and standard errors of parameter estimates were adjusted for over-dispersion (due to between-haul variation) using the replicate estimate of dispersion (Millar and Fryer, 1999). This was calculated by summing the deviances that resulted from fitting the combined-tows selection curve to the data from each individual tow, and dividing by the appropriate degrees of freedom. Wald statistics were calculated for pairwise differences between codends in the estimated parameter vectors (length at 50% retention, L_{50} and selection range, SR) (Kotz et al., 1982). These have an approximate chi-squared distribution (2 d.f.) under the hypothesis of no difference in true L_{50}'s and SRs of the two codends being compared.

3. Results

ANOVA failed to detect any significant differences in weights of prawns for the main effect of codend (Fig. 3A, B, E and Table 1). Significant F ratios were detected for the number of total school prawns caught and the percentage discarded, weight of bycatch and the number of bycatch species, king prawns, southern herring, whitebait, pink-breasted siphonfish and bottle squid (Table 1). SNK tests failed to detect any significant order among codends for the number of total school prawns, although incrementally fewer were caught in the 100 diamond, tapered square and non-tapered square codends, respectively (Fig. 3C). Compared to the 200 diamond codend, all other designs caught significantly less bycatch (means reduced by between 31 and 51%) and fewer southern herring (by 56–82%), whitebait (by 75–99%) and pink-breasted siphonfish (by 42–94%) (Fig. 3G, I–K). The two square-mesh codends similarly caught significantly fewer bycatch species, whitebait, pink-breasted siphonfish and bottle squid than the 100 diamond codend (means reduced by between 34 and 98%) (Fig. 3H, J, K and N), while proportionally fewer school prawns were discarded from the non-tapered square codend than all other designs (Fig. 3D). Several variables had significant F ratios for the main effect of days, but no interactions were detected (Table 1).

The sizes of school and eastern king prawns caught ranged from 3 to 22 mm CL. ANCOVA failed to detect significant differences in regression coefficients or elevations between regressions of log wt and log CL for male ($\log wt = 2.903 \log CL – 6.868$, $r^2 = 0.93$, $n = 178$) and female ($\log wt = 2.922 \log CL - 6.942$, $r^2 = 0.94$, $n = 296$) school prawns and male ($\log wt = 2.939 \log CL - 7.282$, $r^2 = 0.96$, $n = 55$) and female ($2.964 \log CL - 7.326$, $r^2 = 0.93$, $n = 50$) eastern king prawns. Common regressions were calculated as $\log wt = 2.917 \log CL - 6.919$ for school prawns and $\log wt = 2.925 \log CL - 7.234$ for eastern king prawns. Because of these results, selectivity analyses were done irrespective of sex.

School prawns, eastern king prawns and southern herring were caught in sufficient quantities in all codends to permit attempts at modelling their selectivity. Large numbers of whitebait were also retained in the 100 and 200 diamond codends, however, convergence errors occurred during analyses, precluding any estimation of model parameters. Similar results occurred for southern herring from the 200 diamond codend and were attributed to a lack of selectivity by these codends for small fish (i.e. they had similar size distributions as those in the control codend, Fig. 4). Selectivity models were fitted for school and eastern king prawns for all codends, although for the 200 diamond codend, these models were not significantly different from the null model (i.e. no selectivity at $P > 0.05$) and so were not presented.

In all cases where selectivity models converged, there was no significant reduction in deviance associated with using a Richard's curve ($P > 0.05$), except for school prawns caught in the tapered square codend. However, this was only marginally significant ($P > 0.04$) and so, to maintain consistency, the simpler logistic model was used throughout. All model fits showed no significant disequilibrium in fishing efficiency (i.e. parameter $P = 0.05$, Table 2) for school and eastern king prawns between the paired codends ($P > 0.05$). The P for herring was similar in both

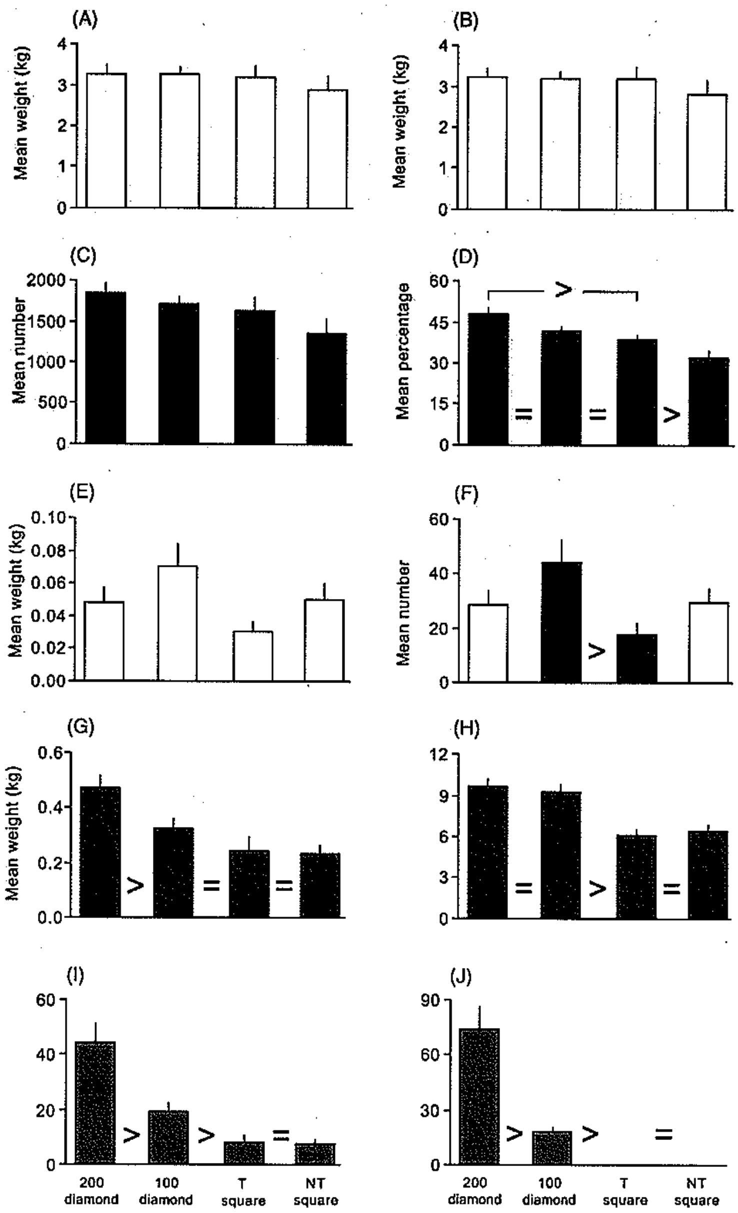

Fig. 3. Differences in mean catch (+S.E.) between the 200 diamond, 100 diamond, tapered square and non-tapered square codends: (A) weight of total prawns, (B) weight and (C) number of total school prawns, (D) percentage of school prawns discarded, (E) weight and (F) number of eastern king prawns, (G) weight of bycatch and numbers of (H) bycatch species, (I) southern herring, (J) whitebait, (K) pink-breasted siphonfish, (L) catfish, (M) Ramsey's perchlet, (N) bottle squid and (O) silver biddy. Shaded histograms represent significant F ratios. > and = indicate the direction of these differences determined by SNK tests.

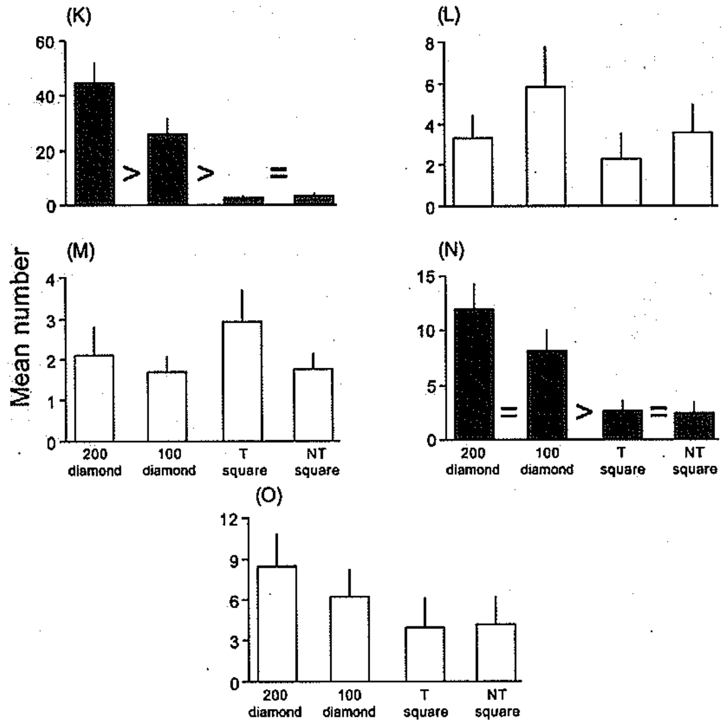

Fig. 3. (*Continued*).

Table 1
F ratios from two-factor ANOVA comparing catches from the four treatment codends fished over 10 days[a]

Source	d.f.	Weight of total prawns	School prawns			King prawns		Bycatch	
			Total		Discarded (%)	Weight	No.	Weight	No.
			Weight	No.					
Days	9	3.94**	3.89**	2.49*	1.67	1.26	0.92	1.98	2.64
Codends	3	1.03	0.99	3.08*	9.49*	2.66	3.25*	8.00**	15.31**
Interaction	27	1.68	1.73	1.73	0.94^{pld}	0.92^{pld}	1.00^{pld}	1.26	0.77^{pld}
Residual	40								
		No. of southern herring	No. of whitebait	No. of PBSF	No. of fork-tailed catfish	No. of Ramsey's perchlet	No. of bottle squid	No. of silver biddy	
Days	9	1.22	1.50	3.39**	0.81	1.53	1.19	2.11	
Codends	3	18.24**	218.50**	58.28**	1.01	0.61	10.09**	2.47	
Interaction	27	0.66^{pld}	0.93^{pld}	1.02^{pld}	0.38^{pld}	0.95^{pld}	0.58^{pld}	1.03^{pld}	
Residual	40								

[a] All data were $\ln(x+1)$ transformed with the exception of percentage of discarded school prawns, which were $\sin^{-1}(\sqrt{x})$ transformed. pld indicates that the F ratio for the interaction was non-significant at $P < 0.25$ and the sums of squares pooled with the residual. The subsequent degrees of freedom (d.f.) for the main effect of codends were 3, 67. PBSF, pink-breasted siphonfish.

* $P < 0.05$.

** $P < 0.01$.

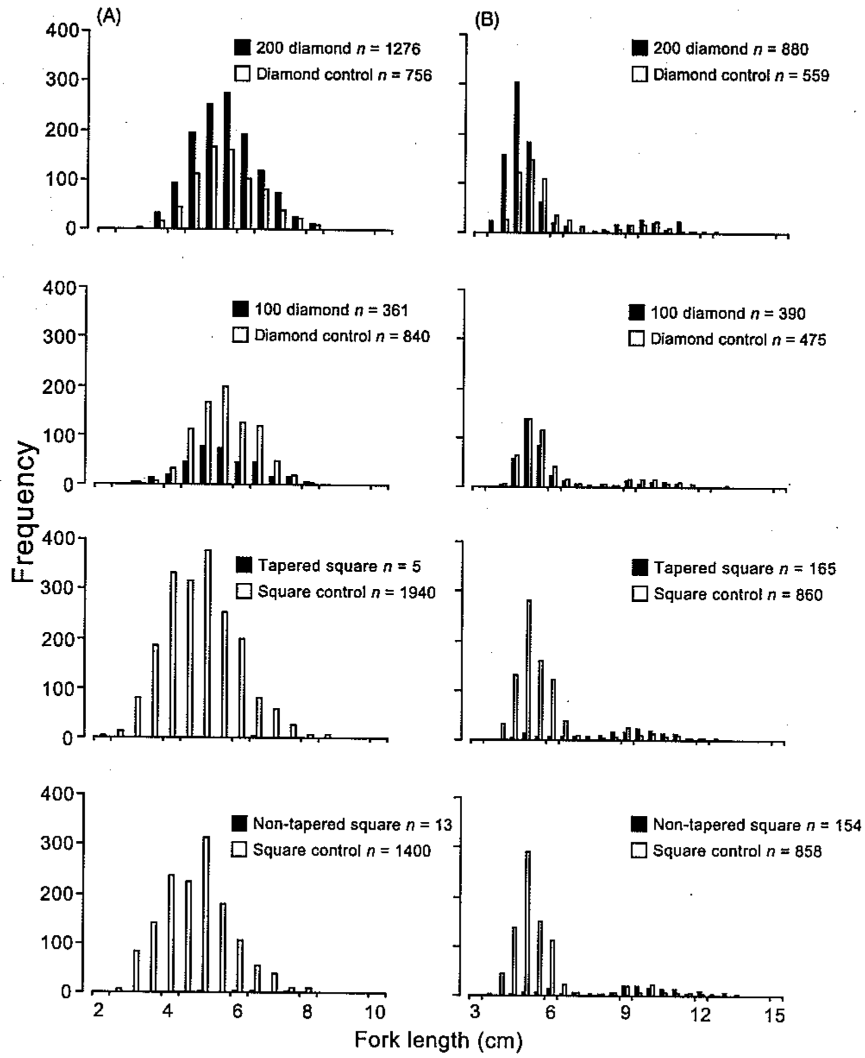

Fig. 4. Size-frequency distributions of (A) whitebait and (B) southern herring from the four experimental codends and their relevant paired controls.

square-mesh codends (i.e. 0.60, Table 2), but only significantly biased in the non-tapered square codend ($P < 0.01$).

The tapered and non-tapered square codends had similar logistic selection curves for school prawns (Fig. 5A and Table 2) and there were no significant differences between estimated L_{50}'s (10.1 and 10.3 mm, respectively) and SRs (3.2 and 3.5 mm) ($P > 0.05$; Table 2). In contrast, the 100 diamond codend had a significantly smaller L_{50} (8.6 mm) and larger SR (3.9 mm) than either square-mesh codend (pairwise χ^2 test, $P < 0.01$) (Fig. 5B and Table 2). All three codends had similar estimated L_{50}'s for eastern king prawns (10.3–10.7 mm) and although the SR for the non-tapered square codend was considerably lower than that for the other designs (i.e. 2.3 vs. 3.5 mm), it

Table 2
Lengths at 50% probability of retention (L_{50}), selection ranges (SRs) and relative fishing efficiencies (P), for school prawns, eastern king prawns and southern herring[a]

	School prawns	Eastern king prawns	Southern herring
100 diamond codend			
L_{50}	8.60 (0.30)	10.30 (0.50)	ns
SR	3.90 (0.60)	3.50 (0.90)	ns
P	0.51 (0.01)	0.52 (0.03)	ns
Tapered square codend			
L_{50}	10.1 (0.20)	10.70 (0.70)	8.00 (0.70)
SR	3.20 (0.30)	3.50 (1.40)	1.60 (0.40)
P	0.48 (0.01)	0.46 (0.04)	0.60 (0.07)
Non-tapered square codend			
L_{50}	10.30 (0.20)	10.6 (0.30)	7.7 (0.40)
SR	3.50 (0.30)	2.30 (0.50)	1.5 (0.30)
P	0.49 (0.01)	0.50 (0.02)	0.60 (0.04)

[a] Lengths are in mm for prawns and cm for southern herring. Standard errors are given in parentheses. The null hypothesis concerning non-selectivity (ns) was not rejected for all three species from the 200 diamond codend and southern herring from the 100 diamond codend.

was not significantly different (pairwise χ^2 test, $P > 0.05$) (Table 2). The estimated selection parameters for southern herring were not significantly different between the two square-mesh codends (pairwise χ^2 test, $P > 0.05$) (Table 2).

4. Discussion

The results illustrate the utility of simple changes in the sizes and configurations of meshes to significantly improve trawl selectivity, measured as a reduction in the unwanted bycatches of fish and small prawns. Compared to the conventional codends, both the square-mesh designs showed a general improvement in performance (Fig. 3 and Table 1). This was due to the escape of nearly all pink-breasted siphonfish and whitebait, along with large number of small individuals of species like southern herring and bottle squid (e.g. up to 82% less than the 200 diamond codend). The magnitude of differences between the diamond and square-mesh codends was accentuated by the extremely poor selectivity characteristics of the former designs, and particularly the conventionally used 200 diamond codend. The lateral mesh openings in these codends were very narrow, and for the 200 diamond codend, these openings were essentially the same as those in the diamond control (20 mm mesh).

Although the selectivities of the tapered and non-tapered square codends were considerably less than the industry-recommended mean target size for school prawns (i.e. 15–17 mm CL), both designs did have significantly greater L_{50}'s and smaller SRs than the 100 diamond codend (Fig. 5A and Table 2). Further, although not significant, the non-tapered square codend similarly selected king prawns over a slightly smaller range of sizes (Fig. 5B and Table 2). These results are consistent with previous studies in fish-trawl fisheries which have shown that SRs for square mesh are generally lower than for diamond mesh (e.g. Robertson and Stewart, 1988; Halliday et al., 1999). The potential for at least some reduction in SR with increasing mesh opening is important because it means that, for the estuarine prawn-trawl fisheries of NSW, it should be feasible to use larger sizes of square mesh (e.g. possibly 23 or 25 mm mesh hung on the bar) and still retain a large proportion of commercial-sized school prawns entering the trawl.

While the improved selectivity of the tapered and non-tapered square codends can be mostly attributed to their larger and more frequent openings, the new novel design and a subsequent maintenance of geometry during fishing probably contributed to their performance. For example, when the codends were retrieved from the water the meshes were observed to remain open throughout the posterior sections, regardless of the catch volume. The posteriorly located circular panels of mesh (that replaced the traditional draw-strings) meant that all individuals entering the codend at least had opportunities to encounter open meshes. In contrast, the traditional diamond-mesh codends with draw-strings were often characterised by bunched and closed meshes and so they probably had varied lateral openings in their posterior sections. It is known that the catch in these sorts of codends tends to spread laterally and assumes a parabolic shape during fishing, effectively masking meshes anterior to the main bulk of catch (Broadhurst et al., 1999a).

Unlike the results observed by Broadhurst et al. (1999b), reducing codend circumference did not improve the selectivity of the square-mesh designs examined here. One possible explanation for this anomaly is that any potential benefits of a narrower codend diameter (e.g. in the tapered square codend) in

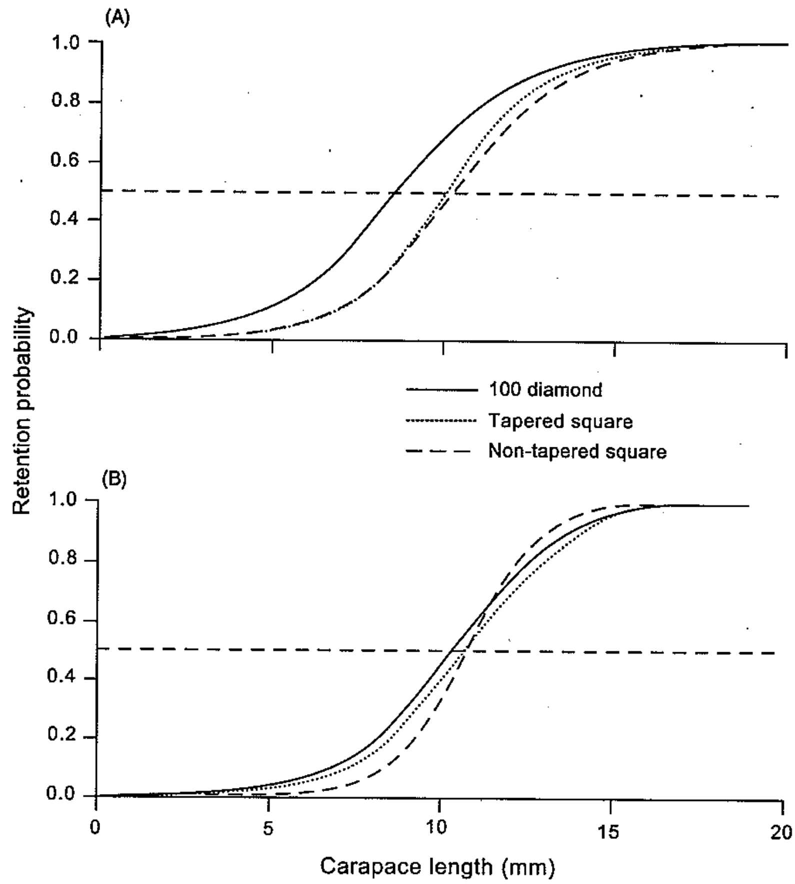

Fig. 5. Logistic selection curves for (A) school prawns and (B) eastern king prawns.

terms of increasing the probability of school prawns encountering open meshes may have been negated by proportionally fewer openings, owing to the size and position of the laterally located 'catch release' zippers (which occupied up to 30% of the surface area of the posterior codend circumference). The potential for this effect could easily be addressed in future modifications by positioning these zippers further forward and away from the accumulation of catch.

The work done in this experiment has shown that the minimum diamond mesh size of 40 mm used in NSW estuarine prawn trawls is entirely inappropriate for the target-sized penaeids. Further, like the results from other studies, this work has shown the potential of square-shaped mesh for significantly improving selectivity (Broadhurst et al., 1999b, 2000). Because similar sizes of diamond-shaped mesh (e.g. 40–50 mm) are used in nearly all prawn-trawl fisheries throughout Australia (but see Broadhurst et al., 1999b, 2000) to target penaeids considerably larger in size than those recorded here (e.g. Broadhurst and Kennelly, 1996b; Brewer et al., 1998; Broadhurst et al., 2002a), it is likely that these fisheries would also benefit from an examination of the effects of increasing mesh openings. Simple modifications to incorporate square-mesh codends in trawls would augment efforts to reduce bycatch in these fisheries.

Acknowledgements

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Modelling between-haul variability in the size selectivity of trawls

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Abstract

The selectivity of fishing gear can vary considerably from set to set even when deployment is replicated under controlled conditions. Analysis of data from size-selectivity experiments will be misleading if this between-deployment variability is not taken into consideration. Here, two approaches are presented for including the effect of between-haul variability when performing size-selectivity experiments for trawls. The first is a simple ad hoc approach that provides a "catch-all" estimate of variability that also takes into account the effect of subsampling the catches. The second is a formal model of random between-haul variability that is fitted via maximum likelihood. The two approaches are applied to both covered-codend and twin-trawl selectivity experiments. The first method is seen to be more intuitive and interpretable, especially when selectivity may depend on catch size, but is limited in its ability to cope with complex experimental designs.

Keywords: Maximum likelihood; Overdispersion; Random effects; SELECT method

1. Introduction

Knowledge of the size (or age) selectivity of fishing gears is crucial for the management, monitoring and efficient exploitation of fisheries. For example, if the mortality of fish that escape the gear is low (relative to discard mortality) then an efficient gear will be one that releases most of the undersized individuals while retaining most of the larger ones. More generally, the retention properties of a fishing gear are quantified by a selectivity curve that gives the probability of retention as a function of fish size (or age).

Replicate tows of trawl gear typically show considerable between-haul variation in size selectivity (Fryer, 1991; Reeves et al., 1992). If this additional variation is not considered when analysing data from size-selectivity experiments then invalid conclusions may result. In particular, uncertainty in parameter estimates will be underestimated and spurious statistical significance is likely to be observed.

Here, we look at two different approaches to modelling between-haul variation when analysing data from size-selectivity experiments on trawl gear, and demonstrate these approaches on data from both covered-codend and twin-trawl experiments where the target species was school prawn (*Metapenaeus macleayi*). The first approach applies an overdispersion correction to the selection curve that is obtained

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from fitting to the catch data summed over all hauls. This selection curve is the same as would be obtained if a single selection curve was simultaneously fitted to all the individual haul data. The fact that the combined-hauls fit is also the fit to the individual hauls permits a replication estimate of between-haul variation (REP) to be calculated.

The second approach is the formal modelling of between-haul variability using a hierarchical mixed-effects model (Fryer, 1991) to explicitly model variation in selectivity parameters between hauls. Here, we take advantage of the NLMIXED procedure available in Version 8 of SAS (SAS Institute, 1999). The NLMIXED procedure uses numerical integration to perform a maximum likelihood fit of the mixed-effects model simultaneously to all the individual haul data. In this regard it differs from the implementation employed by Fryer (1991) which requires the individual haul data to be modelled one haul at a time prior to fitting a mixed-effects model to the estimated selectivity parameters of each individual haul.

For paired-trawl experiments (e.g. alternate hauls, twin trawls, trouser trawls), the above approaches must be modified to include estimation of the relative efficiency parameter, p, of each haul (Millar and Walsh, 1992; Millar and Fryer, 1999). In particular, it is shown that the maximum likelihood estimate (MLE) of p can be calculated explicitly if the selection curve is logistic and this permits easy computation of REP for the combined-hauls fit to paired-trawl data. For the mixed-effects model approach, p can be modelled as an additional random effect.

It is worth noting that both approaches require the dataset or spreadsheet of catch data to be organised in the same way, notwithstanding that when subsampling occurs, the combined-hauls approach uses scaled catch data and the mixed-effects approach uses the unscaled data. Specifically, the data from the hauls should be "stacked" vertically. For example, the covered-codend example used below uses catch data from 19 hauls with 18 lengthclasses measured per haul. The data are organised in a dataset with 342 rows (equal to 19×18) and three or more columns. The minimum set of columns would be lengthclass, codend catch and cover catch. Additional columns need to be added to include relevant covariates such as haul number, subsampling fraction (if only a sample of the catch is measured), gear type, catch weight, etc.

2. Methods

2.1. Combined-hauls fit applied to scaled individual-haul data

It is important to note that if subsampling of catches occurs then the scaled-up data are used because these provide an unbiased estimate of the true total catch when combined over hauls. However, scaling up of the measured catch data gives an inflated sample size that will result in underestimation of uncertainty in the fitted selection curve. This underestimation can be severe if the sampling fractions are small. The REP estimate of overdispersion presented here provides a "catch-all" correction for the variability in the data. In addition to compensating for the effects of between-haul variation and of possible extra-Poisson variation in the measured catches, it also incorporates the effect of the inflated sample size if the measured data are scaled up.

The notation used below applies to both covered-codend and paired-trawl experiments. Specifically, for lengthclass l and haul h, n_{l1}^h denotes the (scaled) catch in the experimental codend, n_{l2}^h denotes the (scaled) catch in the cover (if a covered-codend experiment) or in the control codend (if a paired-trawl type experiment), and $n_{l+}^h = n_{l1}^h + n_{l2}^h$. The notation $\hat{y}_l^h$ is used to denote the proportion of the total catch (i.e. experimental codend plus cover/control) of lengthclass l fish that is expected to be taken in the experimental codend according to the given model of selectivity. The expected catch in the experimental codend is therefore given by $n_{l+}^h \hat{y}_l^h$.

Here, a single selection curve is fitted to the combined-hauls data, and then this curve is used to provide the expected catches for the individual hauls. In the case of covered codends, the $\hat{y}_l$ values are given by the selection curve fitted to the combined-hauls data, and the h superscript can be omitted. However, in the case of paired trawls, these expected proportions also depend on the relative fishing efficiency (Millar and Fryer, 1999) of the experimental codend and control, and this will be permitted to vary between hauls. Consequently, $\hat{y}_l^h$ will depend on h for paired-trawl data.

The replication estimate of overdispersion (REP) is given by evaluating how well the expected catch, calculated using the selection curve fitted to the combined-hauls data, fits the observed catches in each individual haul. That is, how well $n^h_{l+}\hat{y}^h_l$ estimates n^h_{l1}. Specifically, REP (McCullagh and Nelder, 1989) is given by calculating the Pearson chi-square statistic for model goodness-of-fit and dividing by its degrees of freedom (d.o.f.). That is,

$$\text{REP} = \frac{Q}{d} \tag{1}$$

where d is the d.o.f. and

$$Q = \sum_l \sum_h \frac{(n^h_{l1} - n^h_{l+}\hat{y}_l)^2}{n^h_{l+}\hat{y}_l(1-\hat{y}_l)} \tag{2}$$

is the Pearson chi-square statistic and the summation is over all hauls and lengthclasses for which there was sufficient catch. (The model deviance could be used instead of the Pearson chi-square statistic and should give a similar estimate of REP.) The value of d is given by the number of terms in the summation minus the number of fitted parameters. It is common practice to restrict the summation to terms for which the expected catches in the codend and cover/control ($n^h_{l+}\hat{y}_l$ and $n^h_{l+}(1-\hat{y}_l)$, respectively) are both greater than or equal to some value ε. This prevents over-inflation of d. (We recommend that ε should be at least 1, and prefer using $\varepsilon = 3$ if the number of terms in (2) is not reduced too dramatically.)

Under the null hypothesis of no extra-Poisson variation, Q has an approximate chi-square distribution on d d.o.f. If this null hypothesis is rejected, standard errors of estimated parameters should be multiplied by $\sqrt{\text{REP}}$.

In principle, fitting to the individual-hauls data as described above would permit the direct inclusion of covariates (e.g. gear type, catch weight). However, although REP is a meaningful and useful measure of total overdispersion, we do not feel that it should be used for formal model fitting. REP has a chi-square distribution when no extra-Poisson variation is present, but otherwise little else can be said about it because of the non-independence of catch data within each haul.

2.2. *Mixed-effects analysis of individual-haul data*

This approach provides a formal model for overdispersion due to between-haul variation, and assumes that the data from each individual haul are Poisson distributed. Therefore, if catches are subsampled, it is the raw (unscaled) data that are used, and the effect of subsampling must be taken into account when fitting the model to these raw data (Millar, 1994; Appendix A).

The mixed-effects methodology incorporates the between-haul variation explicitly by letting each haul have its own set of parameters. For covered-codend experiments these parameters are just the parameters of the selection curve. In the case of paired trawls, the parameters also include the relative fishing efficiency of the experimental codend. The general notation used here will be to denote the set of parameters for haul h by $\nu^h = (\nu^h_1, \ldots, \nu^h_q)^T$. For example, if fitting logistic selection curves to data from a covered-codend experiment then the curve can be specified by its length of 50% retention, l_{50}, and selection range, SR, in which case $\nu^h = (l^h_{50}, \text{SR}^h)^T$. In the case of a paired-trawl experiment, $\nu^h = (l^h_{50}, \text{SR}^h, p^h)^T$, where p^h is the probability that a fish entered the experimental codend of paired haul h, given that it entered one or other of the codends.

The mixed-effects model of selectivity treats between-haul variation as a random effect and the parameters for each haul vary randomly about a mean vector of parameters. Controlled changes to the gear (e.g. changes in mesh size or shape) are also modelled, as fixed effects, by allowing the mean parameters to change in a systematic way. Specifically, it is assumed that the haul parameters vary from haul to haul according to the model

$$\nu^h = \theta^h + \epsilon^h \tag{3}$$

where θ^h is the $q \times 1$ vector of expected parameter values for the selection curve of the gear used in haul h and ϵ^h the $q \times 1$ random vector representing the random variation in the actual parameters for haul h.

The ϵ^h are assumed to be independent and multivariate normally distributed with zero mean and constant, but unknown, $q \times q$ variance matrix D. Thus, ν^h has a multivariate normal distribution with mean θ^h and variance D. That is,

$$\nu^h \sim N_q(\theta^h, D)$$

Mixed-effects models can be very difficult to fit because calculating the likelihood function for the parameters of the fixed effects and D requires "averaging" over all possible values of the random-effects vectors, ϵ^h. This corresponds to a problem of high-dimensional integration and is tractable only in special cases (such as linear mixed models with normal data). It is not tractable for selectivity data because the data are non-normal and the models are non-linear.

An alternative, which has been widely used in practice (Fryer, 1991; Reeves et al., 1992; Galbraith et al., 1994; Madsen et al., 2002) is to use the selection parameters and associated covariances estimated from each individual haul, and to model these according to a linear mixed model (Laird and Ware, 1982). Effectively, the "data" for each haul are reduced to the MLE $\hat{\nu}^h$ (and its covariance matrix), and Eq. (3) is fitted to these reduced "data" with θ^h required to be a linear function of gear covariates.

More recently, there is now software available that can fit more general forms of mixed models using numerical quadrature techniques to approximate the underlying high dimensional integrals. In particular, here we report on application of SAS procedure NLMIXED (SAS Institute, 1999) for modelling between-haul variability in both covered-codend and paired-trawl experiments.

3. Application to covered-codend data

The catch data are from 19 covered-codend lifts of a stow net with an experimental codend constructed from 30 mm knotted square mesh, done in the Clarence River, New South Wales, during July and August 2002. School prawns (*M. macleayi*) in the codend and cover were measured to the nearest millimetre carapace length, up to a maximum of approximately 250 animals each. For a full description of the methodology used during the experiment and a general overview of the Clarence River stow net fishery, refer to Macbeth et al. (2003) and Andrew et al. (1995), respectively.

For exploratory purposes, the individual-set data were modelled using individual logistic selection curves. These provided a good fit and lack of fit was not detected in any of the 19 individual fits. The l_{50}'s from the individual fits ranged from about 12 to 18 mm, and the selection ranges varied from about 2.5 to 10 mm (Fig. 1), notwithstanding that the higher estimated selection ranges also had high standard errors. In particular, for sets 10, 18 and 19, the standard errors of the estimated l_{50} and SR were relatively high, due to very small catches. Plots of the individual-set estimates against codend catch weight suggest a weak relationship if any (Fig. 1).

3.1. Combined-hauls fit to individual-haul data

A single selection curve was fitted to the combined data (summed over hauls after scaling for subsampling of catches). The model deviance was 23.5 on 15 d.o.f. for a logistic selection curve, and 13.3 on 14 d.o.f. for a Richards selection curve. The model deviances from fitting to combined-hauls data will not satisfy the usual assumption of being approximately chi-square distributed, however, they still provide a clear quantification of relative lack of fit around the estimated combined-hauls selection curve. Deviance residuals from the logistic curve showed obvious lack of fit, which was not evident in the residual plot from the Richards fit. Hence, the Richards fit was used (Table 1).

A Richards selection curve was then fitted to the scaled individual-haul data (stacked vertically as explained in Section 1). These are exactly the same data as used in the combined-hauls fit, except that they are broken down by replicate haul, and consequently the fitted Richards curve and estimated standard errors were exactly the same as those obtained from the combined-hauls fit. The Pearson chi-square statistic from this fit was 993.2 on 99 d.o.f. when restricting the summation in Eq. (2) to terms with expected counts in experimental codend and cover of at least 3. This gives a REP of 10.03. Correcting for this amount of extra-Poisson variation, the standard errors estimated

Table 1
Combined-hauls and mixed-effects model fits to the covered-codend catches of school prawn[a]

Method	Parameters	Estimate	S.E.
Combined hauls	REP	10.03	
	l_{25}	13.16	0.77
	l_{50}	16.17	0.20
	l_{75}	18.34	0.22
	SR	5.17	0.85
Mixed model	$\mu_{l_{50}}$	15.52	0.31
	μ_{SR}	4.02	0.16
	$\sigma^2_{l_{50}}$	1.66	0.57

[a] The combined-hauls selection curve is of Richards' form, and the standard errors of its estimated parameters have been multiplied by $\sqrt{REP} = 3.17$.

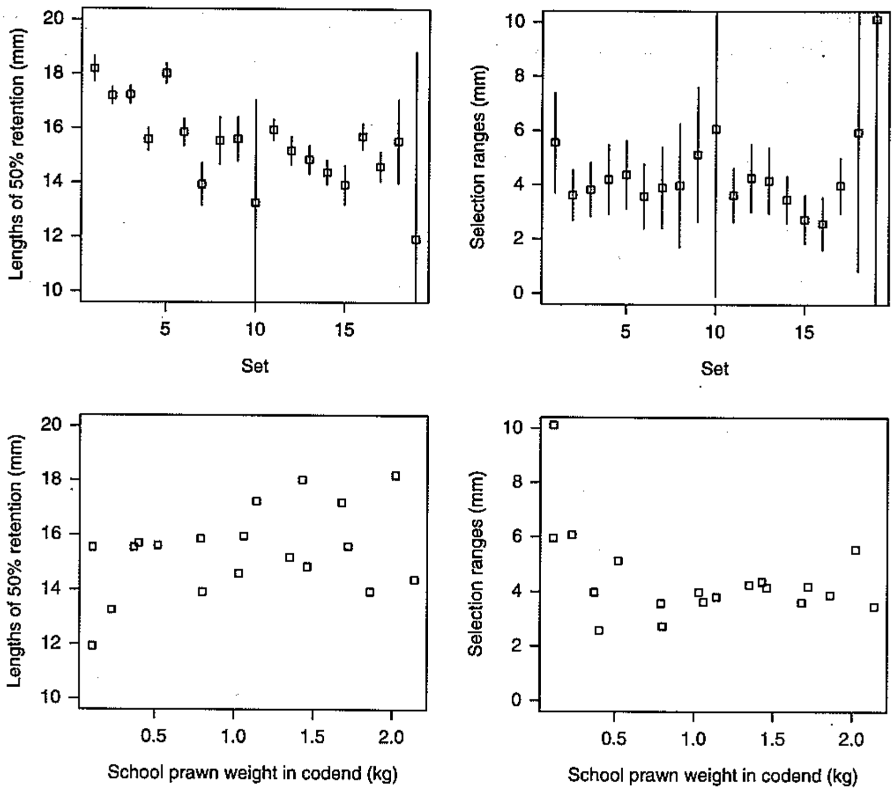

Fig. 1. Estimates of the 50% retention length and selection range for the 19 individual covered-codend sets of stow nets with 30 mm square-mesh experimental codends. Top row: estimates plotted in order of deployment, with approximately 95% CIs (i.e. ±1.96 S.E.). Bottom row: estimates plotted against catch weight of school prawns.

from the fit were multiplied by a factor of $\sqrt{10.03} \approx 3.17$ (Table 1).

3.2. Mixed-effects model

A mixed-effects analysis was implemented using PROC NLMIXED. Logistic curves were used because they had adequately fitted the individual-haul data. Catch weight (kg) of school prawn in the codend was used as a covariate to model l_{50} and SR,

$$l_{50}^h = \mu_{l_{50}} + \theta_1 w^h + \epsilon_1^h \quad (4)$$

$$\mathrm{SR}^h = \mu_{\mathrm{SR}} + \theta_2 w^h + \epsilon_2^h \quad (5)$$

where w^h is log(catch weight+1) of school prawns and $(\epsilon_1^h, \epsilon_2^h)^{\mathrm{T}}$ are bivariate normal with zero mean vector and 2×2 variance matrix D.

PROC NLMIXED would not converge for an arbitrary variance matrix D, but did converge when the covariance between ϵ_1^h and ϵ_2^h was assumed to be zero, and this fit had a log-likelihood of −349.5 (see Appendix A for the PROC NLMIXED code used to fit this model). A simpler model without the catch weight parameters θ_1, θ_2, and with $\sigma_{\mathrm{SR}}^2 = \mathrm{Var}(\epsilon_2^h) = 0$ (i.e. no between-haul variability in selection range) had log-likelihood of −350.0 and hence was preferable (Table 1).

4. Application to paired-trawl data

The data are catches of school prawns (*M. macleayi*) from 60 twin-trawl hauls conducted in March 2002 in Lake Woolooweyah in New South Wales (see Broadhurst et al., 2004). Twenty hauls used an experimental 40 mm knotted diamond-mesh codend. The other 40 hauls used experimental codends constructed from unknotted 20 mm square mesh, with 20 of these hauls using a tapered codend (tapering from 110 bar circumference to 54 bar at the end of the posterior section) and 20 using an untapered codend (110 bar circumference throughout). School prawns in both experimental codend and control were measured to the nearest millimetre carapace length, up to a maximum of 250 animals.

An exploratory look at the l_{50}'s and SRs from logistic selection curve fits to the 60 individual hauls suggests that the diamond-mesh codend may have a smaller l_{50} than the square-mesh codends. There is also some suggestion of l_{50} decreasing with catch weight in the untapered square-mesh codend (Fig. 2).

4.1. Combined-hauls analysis of individual haul data

Analysis of paired-trawl data includes an additional parameter, p, the probability that a fish entering the paired trawl will enter the experimental codend. Here, a separate p^h for each haul was fitted.

Estimation of Q (Eq. (2)) was done in two steps. First, a selection curve, $\hat{r}(l)$ was fitted to the (scaled) data combined over all hauls. Second, using $\hat{r}(l)$, the MLE of p^h was calculated for each individual

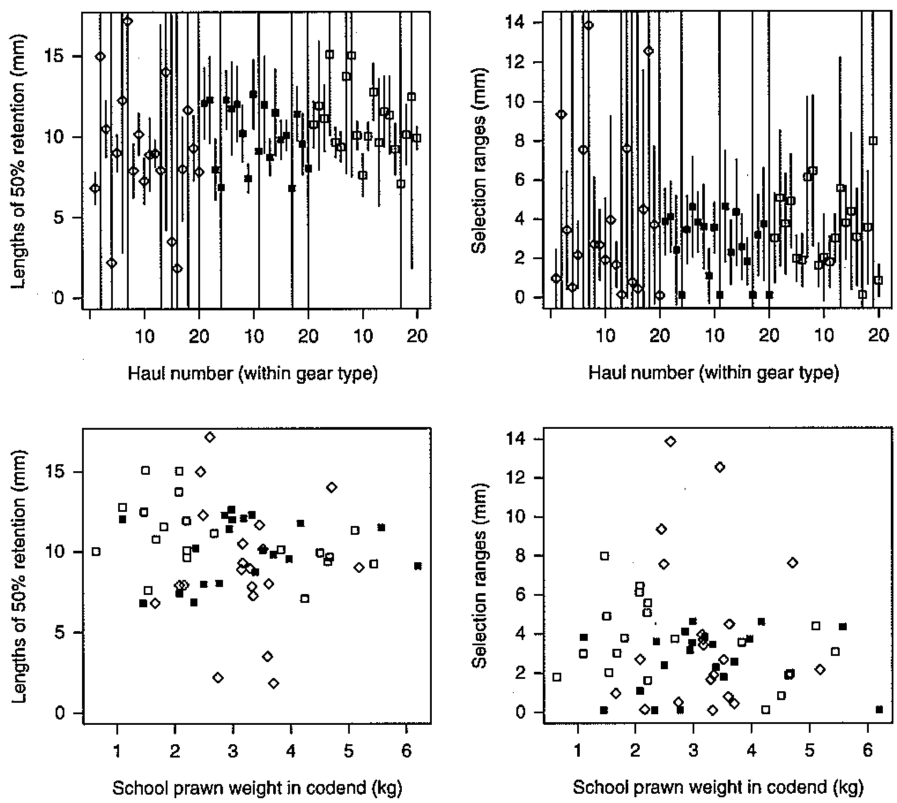

Fig. 2. Estimates of the 50% retention length and selection range for the 60 individual twin-trawl hauls consisting of 20 hauls each with the experimental codend made from diamond mesh (diamond plot symbol), tapered square mesh (solid square symbol), and untapered square mesh (open square symbol). Top row: estimates plotted in order of deployment within each gear type, with approximately 95% CIs (i.e. ±1.96 S.E.). Bottom row: estimates plotted against catch weight of school prawns.

hauls. When $\hat{r}(l)$ is a selection curve of logistic form then the MLE of p^h can be obtained explicitly (Appendix B),

$$\hat{p}^h = \frac{\sum_l n_{l1}^h}{\sum_l (n_{l1}^h + n_{l2}^h \hat{r}(l))} \tag{6}$$

This equation may not be exact for non-logistic selection curves, but will still provide an extremely accurate approximation that should be more than adequate in practice.

With $\hat{p}^h$ calculated as above, the proportion of length l prawns that is expected to be caught in the experimental codend is given by (Millar and Walsh, 1992)

$$\hat{y}_l^h = \frac{\hat{p}^h \hat{r}(l)}{\hat{p}^h \hat{r}(l) + (1 - \hat{p}^h)} \tag{7}$$

from which Q can be calculated using Eq. (2). When calculating REP it is necessary to deduct an additional degree of freedom for each estimated $\hat{p}^h$.

For the prawn data of Broadhurst et al. (2004), the combined-hauls data from the diamond and tapered square-mesh codends were well fitted by logistic selection curves and fits of Richards selection curves were almost identical. The logistic fit to the untapered square-mesh data showed some lack of fit, and when compared to the Richards curve, the difference in model deviance resulted in a p-value of 0.04 (notwithstanding that this p-value should be regarded as indicative only). Using the Bonferroni correction for three comparisons, a p-value must be less than $0.05/3 = 0.01667$ to reject the null hypothesis at the 5% level, hence the logistic selection curve was used for all three codends. The Q values for the diamond, tapered square, and untapered square-mesh codends were 2274 on 266 d.o.f., 2886 on 261 d.o.f., and 2242 on 254 d.o.f., respectively. These correspond to REP values of 8.55, 11.06, and 8.83, respectively (Table 2).

Broadhurst et al. (2004) used the Wald statistic (Kotz et al., 1982) to test equality of the selection curves for the three gears. They found that the selection curve of the diamond-mesh codend was significantly different ($p < 0.001$) from the selection curves of the square-mesh codends, and that the selection curves of the two square-mesh codends were not significantly different ($p = 0.71$).

Table 2
Combined-hauls fits to the twin-trawl catches of prawn[a]

Gear	Parameters	Estimate	S.E.
40 mm diamond	REP	8.55	
	l_{25}	6.62	0.33
	l_{50}	8.56	0.26
	l_{75}	10.50	0.45
	SR	3.88	0.59
20 mm tapered square	REP	11.06	
	l_{25}	8.52	0.15
	l_{50}	10.10	0.21
	l_{75}	11.68	0.32
	SR	3.15	0.27
20 mm untapered square	REP	8.83	
	l_{25}	8.53	0.17
	l_{50}	10.28	0.24
	l_{75}	12.02	0.37
	SR	3.49	0.34

[a] All selection curves are logistic. The standard errors have been multiplied by $\sqrt{\text{REP}}$.

4.2. Mixed-effects model

The mixed-effects Eqs. (4) and (5) were used to model l_{50}^h and SR^h, respectively. In addition, the relative efficiency parameters were modelled as

$$\text{logit}(p^h) = \log\left(\frac{p^h}{1 - p^h}\right) = \mu_\text{p} + \epsilon_3^h \tag{8}$$

where each ϵ_3^h is normal with mean zero and variance σ_p^2, and is assumed to be independent of ϵ_1^h and ϵ_2^h.

PROC NLMIXED exhibited convergence problems when attempting to fit the model specified by Eqs. (4), (5) and (8) to the data from the three gears. Instead, the model was fitted separately to each gear. Once again, PROC NLMIXED would not converge when an arbitrary variance matrix D was specified, but did converge when the covariance between ϵ_1^h and ϵ_2^h was assumed to be zero. From the fits to the individual gears, it was found that the simpler model without the parameters θ_1, θ_2 and $\sigma_\text{SR}^2 = 0$ (i.e. no between-haul variability in SR) was preferable (Table 3). This model had parameters $\mu_{l_{50}}$, μ_SR, μ_p, $\sigma_{l_{50}}^2$, and σ_p^2 (Table 3).

Further experimentation with PROC NLMIXED revealed that it was possible to fit the above model simultaneously to the data from all three gears while using separate $\mu_{l_{50}}$ and μ_SR parameters for each gear and common μ_p, $\sigma_{l_{50}}^2$ and σ_p^2 parameters for all three

Table 3
Forward selection of mixed-effects fits to the twin-trawl catches of prawn[a]

Gear	Parameters	Negative log-likelihood	p-Value
40 mm diamond	$(\mu_{l_{50}}, \mu_{SR}, \mu_p)$	701.99	
	$(\mu_{l_{50}}, \mu_{SR}, \mu_p, \sigma^2_{l_{50}})$	684.31	<0.001
	$(\mu_{l_{50}}, \mu_{SR}, \mu_p, \sigma^2_{l_{50}}, \sigma^2_p)$	677.33	<0.001
	$(\mu_{l_{50}}, \mu_{SR}, \mu_p, \sigma^2_{l_{50}}, \sigma^2_p, \sigma^2_{SR})$	676.42	0.089
	$(\mu_{l_{50}}, \mu_{SR}, \mu_p, \sigma^2_{l_{50}}, \sigma^2_p, \theta_1, \theta_2)$	675.25	0.125
20 mm tapered square	$(\mu_{l_{50}}, \mu_{SR}, \mu_p)$	749.61	
	$(\mu_{l_{50}}, \mu_{SR}, \mu_p, \sigma^2_{l_{50}})$	695.57	<0.001
	$(\mu_{l_{50}}, \mu_{SR}, \mu_p, \sigma^2_{l_{50}}, \sigma^2_p)$	682.97	<0.001
	$(\mu_{l_{50}}, \mu_{SR}, \mu_p, \sigma^2_{l_{50}}, \sigma^2_p, \sigma^2_{SR})$	681.40	0.038
	$(\mu_{l_{50}}, \mu_{SR}, \mu_p, \sigma^2_{l_{50}}, \sigma^2_p, \theta_1, \theta_2)$	682.55	0.657
20 mm untapered square	$(\mu_{l_{50}}, \mu_{SR}, \mu_p)$	890.56	
	$(\mu_{l_{50}}, \mu_{SR}, \mu_p, \sigma^2_{l_{50}})$	699.45	<0.001
	$(\mu_{l_{50}}, \mu_{SR}, \mu_p, \sigma^2_{l_{50}}, \sigma^2_p)$	692.37	<0.001
	$(\mu_{l_{50}}, \mu_{SR}, \mu_p, \sigma^2_{l_{50}}, \sigma^2_p, \sigma^2_{SR})$	692.21	0.286
	$(\mu_{l_{50}}, \mu_{SR}, \mu_p, \sigma^2_{l_{50}}, \sigma^2_p, \theta_1, \theta_2)$	688.49	0.021

[a] Using the Bonferroni correction for testing across the three gears, a p-value of 0.0167 or less is required for a term to be considered significant at the 5% level. The tests for variance components are one-sided. The model selected as most appropriate for all three gears has parameters $(\mu_{l_{50}}, \mu_{SR}, \mu_p, \sigma^2_{l_{50}}, \sigma^2_p)$.

Table 4
Mixed-effects fits to the twin-trawl catches of prawn

Gear	Parameters	Estimate	S.E.
40 mm diamond	$\mu_{l_{50}}$	8.08	0.40
Both 20 mm square	$\mu_{l_{50}}$	10.23	0.27
All gears	μ_{SR}	3.48	0.17
	μ_p	0.0025	0.034
	$\sigma^2_{l_{50}}$	2.02	0.53
	σ^2_p	0.038	0.01

gears, for a total of nine parameters. This model had a log-likelihood of −2054.63. A simpler model with common μ_{SR} for all three gears and a common $\mu_{l_{50}}$ for the two square-mesh codends (a total of six parameters) reduced the log-likelihood by just 1.06 and hence this simpler model was preferred (Table 4). The parameter μ_p was not statistically significant in this model, but we elected to retain it to avoid any bias that may arise if μ_p were set equal to zero.

5. Discussion

Estimates of selectivity parameters can differ somewhat between the two methods demonstrated here. This is not unexpected because the two methods are modelling different things. The combined-hauls approach is giving a simple quantification of "fisheries" selectivity, in the sense that it is an appropriate estimate of the contact-selection curve (Millar and Fryer, 1999) relevant to the fishery. This interpretation assumes that, when used in the fishery, deployment of the experimental codend and catch sizes will be similar to that experienced during the selectivity study. This selection curve would be suitable for use in studies of incidental mortality, say. The mixed-model approach is describing the structure and variability in individual hauls, and parameters such as $\mu_{l_{50}}$ and μ_{SR} are not directly relevant to the selectivity of the experimental gear on the fishery. The mixed-model approach provides a formal method for modelling the effect of covariates. These could be observed covariates such as catch weight, or design covariates such as mesh size, hanging ratio, etc.

In the covered-codend example the value of SR estimated from the combined-hauls approach was substantially higher than the mean SR value estimated by the mixed-effects approach (Table 1). This is perhaps not surprising because between-haul variability tends to smear the effect of individual-haul selectivity. It was also the case that the estimated l_{50} and

$\mu_{l_{50}}$ differed noticeably in the covered-codend experiment (16.17 and 15.52 mm, respectively) and for the diamond-mesh codend in the twin-trawl experiment (8.56 and 8.08 mm, respectively). This may be due to the fundamentally different way in which the two approaches statistically weight the data from each haul. The combined-hauls approach uses the scaled data and hence has the appealing property of weighting the data from each haul according to the catch weight in that haul. The more formal mixed-effects approach models the raw data and hence weights each haul equally (assuming sufficient catch to meet the sampling requirements). For the covered-codend data, it was noticed that the smallest two sampling fractions occurred for the catches in the covers in sets 1 and 5. These two sets had the largest l_{50}'s of the 19 sets (Fig. 1). The combined-hauls analysis would have given these catches higher statistical weight than the mixed-effects analysis, resulting in a higher estimated l_{50}.

The above paragraphs highlight the need to understand the underlying differences between the combined-hauls and mixed-effects approaches, and to make an informed choice of which method to use. This choice may well depend on the objectives of the study and the intended use of the estimated selection curve(s). If the selectivity experiment involves a single gear then it may be enough to use the straightforward combined-hauls approach in conjunction with the calculation of REP.

If the selectivity experiment involves multiple gears then the choice between combined-hauls analysis or mixed-effects analysis may not be as easy. Fitting the mixed-effects model using software such as PROC NLMIXED is a more rigorous approach, but does require more assumptions regarding the form of the model. If selectivity of individual hauls is dependent on catch size then the concept of a mean l_{50} and SR makes little sense and it is vital that the mixed-effects model includes catch weight as a covariate so that the these mean parameters are explicitly modelled as a function of catch weight. Unfortunately, we found here that the data did not permit PROC NLMIXED to fit models with many parameters or any covariance terms, and the simultaneous modelling of several gears and associated covariates may not always be possible using this software.

An alternative implementation of the mixed-effects methodology is to use the linear mixed-effects approach employed by Fryer (1991). This requires maximum likelihood fits to the data from each individual haul and this can be problematic, particularly when some hauls have limited data. For paired trawls this does have the advantage of estimating p^h at the individual haul level and thereby avoiding the need to model p^h in the mixed-effects model. However, this approach relies crucially on the assumption that the estimated selectivity parameters from the individual fits are (approximately) normally distributed with covariance matrix well estimated from the asymptotic covariance matrix. Like the mixed-effects approach used herein, this approach does not weight individual hauls according to the size of catch, and one would need to include catch weight as a covariate if it has an effect on selectivity (e.g. Madsen et al., 2002).

Acknowledgements

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Appendix A

SAS code for the mixed-effects fits to the covered-codend and paired-trawl data. Variable `haul` is the haul number and variables `lenclass`, `wgt`, `q1`, `q2` are the lengthclass, log(catch weight + 1) in codend, and sampling fractions of the experimental codend and cover/control, respectively. For covered-codend data, `cover` is the catch in the cover, and for paired-trawl data, `control` is the catch in the control codend. Variable `codend` contains the catch in the experimental codend.

A.1. Covered codend

```
PROC NLMIXED DATA=CoveredCodend
  METHOD=GAUSS ABSGCONV
        =0.000001[3];
  total=codend+cover;
```

```
work=(q1/q2)*exp(2*log(3)
      *(lenclass-(meanL50+L50
      +theta1*wgt))/
      (meanSR+SR+theta2*wgt));
r=work/(1+work);
PARMS meanL50=15 meanSR=3 theta1
            =0 theta2=0;
MODEL codend ~ BINOMIAL(total,r);
RANDOM L50 SR~ NORMAL([0,0],
[varL50,0,varSR]) SUBJECT=haul;
RUN;
```

A.2. Paired trawl

Here, Sq is an indicator variable that takes the value 1 for the tapered or untapered square-mesh codends, and 0 otherwise.

```
PROC NLMIXED DATA=TwinTrawl METHOD
  =GAUSS ABSGCONV=0.000001[3];
  total=codend+control;
  work=exp(2*log(3)
      *(lenclass-(meanL50+L50
      +Sq*DSqL50))/(meanSR));
  r=work/(1+work);
  peta=meanPeta+P;
  psplit=exp(peta)/(1+exp(peta));
  phi=q1*psplit*r/(q1*psplit*r
     +q2*(1-psplit));
  PARMS meanL50=8.2 DSqL50
    =1.7 meanSR=4.0 meanPeta
    =0 varL50=2 varP=1;
  MODEL test ~ BINOMIAL(total,phi);
  RANDOM L50 P~ NORMAL([0,0],
    [varL50,0,varP]) SUBJECT=haul;
RUN;
```

Appendix B

The log-likelihood function for paired-trawl data is

$$\log(L) = \sum_l \left\{ n_{l1} \log\left(\frac{pr(l)}{(1-p)+pr(l)}\right) + n_{l2} \log\left(\frac{1-p}{(1-p)+pr(l)}\right) \right\}$$

If the selection curve is logistic then it can be written as

$$r(l) = \frac{e^{a+bl}}{1+e^{a+bl}}$$

and (after a bit of calculus),

$$\frac{\partial \log(L)}{\partial a} = \sum_l \frac{(n_{l1}(1-p) - n_{l2}pr(l))(1-r(l))}{(1-p)+pr(l)}$$

$$= \sum_l \frac{n_{l1}((1-p)+pr(l)-r(l)) + n_{l2}r(l)((1-p)+pr(l)-1)}{(1-p)+pr(l)}$$

$$= \sum_l \left\{ n_{l1} + n_{l2}r(l) - \frac{n_{l+}r(l)}{(1-p)+pr(l)} \right\}$$

At the MLE the above derivative is zero, giving

$$\sum_l (n_{l1} + n_{l2}r(l)) = \sum_l \frac{n_{l+}r(l)}{(1-p)+pr(l)} \quad \text{(B.1)}$$

Differentiating $\log(L)$ with respect to p, and using (B.1), gives

$$\frac{\partial \log(L)}{\partial p} = \frac{1}{p(1-p)} \sum_l \frac{n_{l1}(1-p) - n_{l2}pr(l)}{(1-p)+pr(l)}$$

$$= \frac{1}{p(1-p)} \sum_l \left\{ n_{l1} - \frac{n_{l+}pr(l)}{(1-p)+pr(l)} \right\}$$

$$= \frac{1}{p(1-p)} \sum_l \{ n_{l1} - p(n_{l1} + n_{l2}r(l)) \}$$

Setting this derivative to zero gives the result that the maximum likelihood estimate of p is

$$\hat{p} = \frac{\sum_l n_{l1}}{\sum_l (n_{l1} + n_{l2}r(l))}$$

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Strategies for improving the selectivity of fishing gears

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Abstract

Few fishing methods and gears are entirely selective for the targeted species and their sizes. The majority of gears have incidental catches (collectively termed 'bycatch') that vary from isolated occurrences in some hook-and-line fisheries to large numbers of juveniles of key species in trawl fisheries. Of primary concern is the contribution that the mortalities of such bycatches may have on subsequent stocks. Over the past 20 years, extensive efforts have been directed towards addressing this issue by modifying problematic fishing gears (especially trawls) and practices. Whilst this work has facilitated considerable reductions in bycatches (up to 80% in some cases), very few (if any) of the changes made to existing gears are 100% effective. There remains, therefore, a substantial mortality of unwanted individuals in most fisheries. To work more comprehensively towards the ultimate goal of achieving perfect selectivity, we propose that, in addition to conventional methods used in recent decades to modify fishing gears, a more lateral approach should also be adopted involving completely alternative gears. Specifically, we propose a strategy that: (1) examines the boundaries of what is realistically achievable in modifying poorly selective gears using established bycatch reduction protocols; and (2) determines the utility of alternative gears that, because of their design and/or operation, have selective mechanisms which could be applied to problematic gears. In this paper, the logic involved in the first approach is discussed and data supporting the benefits of the second approach are presented.

The issue of bycatch

From the earliest evidence of fishing more than 90 000 years ago (Yellen et al. 1995) to the present day, humans have exponentially advanced their harvesting methods. The clear focus of these developments has been to maximize the catches of an ever-increasing diversity of targeted species, with little or no regard for the incidental catches (termed 'bycatch', sensu Saila 1983). A progression from simple harpoons, hooks and traps deployed from the shore, through nets set from boats, to the industrial factory trawlers of developed countries has culminated in technology which, in many cases, far exceeds the sustainability of local resources. This excess was evident at the end of the 20th century by the collapse of many commercially-important stocks, a plateau in the world's total landed wild catch (at less than 100 million tonnes) and the volumes of bycatch discarded in pursuit of targeted catches (Alverson et al. 1994).

While recognition of the potentially negative impacts of unchecked fishing technology date back to the 14th century (Dyson 1977), it is only during the last few decades that coordinated attempts have been directed towards improving the selectivity of fishing gears (Kennelly and Broadhurst 2002). Relevant reviews of the published literature suggest that nearly all fishing gears and methods have received at least some attention (e.g. gillnets – Hamley 1975; longlines – Løkkeborg and Bjordal 1992; traps – Mahon and Hunte 2001), although the majority of effort has been directed towards benthic trawl fisheries (e.g. Kennelly 1995) and especially those targeting shrimp (Andrew and Pepperell 1992; Broadhurst 2000). This has occurred in response to the disproportional ratio of retained-to-discarded catches and the amount of unwanted catch discarded each year by shrimp trawlers; estimated to represent between 30 and 60% of the total world harvest of wild fisheries resources (Alverson et al. 1994). While the absolute volume of bycatch associated with shrimp trawling clearly makes it one of the most the most problematic fishing methods, many other gears including fish trawls, seines, gillnets, traps and longlines have, in recent times, been identified as having significant selectivity issues and have consequently been associated with prolonged calls for improvements coming from a variety of environmental groups, recreational fishers, interacting commercial fisheries and the general public.

Solving bycatch problems

During the past 2 decades, problems surrounding the issue of bycatch has shifted the focus of fishing gear technology from catching as much of the target species as possible (with little regard for collateral impacts) to improving selectivity, both in terms of the species targeted and their desired sizes (Kennelly and Broadhurst 2002). In many cases, the successful development and adoption of solutions to improve selection in problematic gears can be summarized in a simple framework (see also Kennelly and Broadhurst 1996; Kennelly 1997; Broadhurst 2000) which involves industry and researchers each applying their respective areas of expertise to the particular problem. This framework comprises five key steps: (1) quantifying bycatches (mostly via observer programs), (2) identifying the main bycatch species and their sizes of concern, (3) developing alterations to existing fishing gears and practices that minimize the mortality of these species, (4) testing these alternatives in appropriately-designed field experiments and (5) gaining acceptance of the new technology throughout the particular fishery and interested stakeholders.

The protocol for completing the framework is quite straightforward and has been described with numerous examples by Kennelly and Broadhurst (1996), Kennelly (1997) and Broadhurst (2000). The crucial and most difficult step (3 above) is the actual development of appropriate solutions that improve the selectivity of existing fishing gears for the targeted catch and so reduce unwanted bycatch. Depending on the type of gear and its particular problems, solutions may involve simple adjustments to operational procedures and/or existing components of the gear, like changing the size and/or shape of meshes or hooks. Alternatively, for many towed gears, more complicated modifications that include physical bycatch reduction devices (BRDs) may need to be invented or modified from other fisheries (Broadhurst 2000). Owing to their relative complexity, these types of modifications frequently require detailed adjustment and reassessment to exclude specific sizes of individuals or species, yet maintain targeted catches (Kennelly and Broadhurst 2002).

While the above framework summarizes several successful attempts at addressing the problems of bycatch in different fisheries throughout the world (Kennelly 1997), in many cases the established protocols for improving inherently problematic gears has restricted fishing technologists in terms of working towards the ultimate goal of perfect selectivity. A reason for this is that to ensure the industry adoption and acceptance of modified designs that reduce bycatch (i.e. step 5 above), nearly all researchers have aimed to achieve 100% retention of the targeted species (during step 3). Theoretically, it should be possible to dramatically improve the selectivity of most fishing gears, provided some concomitant sacrifice in their overall efficiency is permitted. The issue would then become what is an acceptable loss of the targeted catch in order to improve selectivity and reduce bycatch. An extreme solution for achieving 'perfect selectivity' may be to reorder the above logic and, using traditional gears and established bycatch reduction methods, approach a 100% exclusion rate of unwanted catch at any cost to the desired catch. This approach could be appropriate in tightly-regulated fisheries where there is imminent threat of closure due to discarding. Reductions in gear efficiency could also be offset via some compensatory increases in the value of the targeted catch through 'eco-labeling'. This sort of strategy would not be feasible, however, in the vast majority of countries and especially those where artisanal fisheries represent the main source of income for communities. For these fisheries, bycatch reduction clearly needs to be maximized with minimal impact on the efficiency of the gear for the targeted catch.

Maximizing gear development within existing bycatch reduction frameworks

To approach maximum bycatch reduction with no loss of the targeted catch (during step 3 of the framework described above), there needs to be a general estimate of what is achievable for particular gears. As a starting point, this requires an assessment of the limits of established modifications for improving selectivity. For many conventional towed gears, different sizes and/or shapes of mesh are among the simplest alterations and their utility is often (or at least should be) defined first. Under the framework proposed by Broadhurst (2000), this involves testing beyond what might intuitively be appropriate, so that the limits of a particular range of mesh sizes or shapes can be quantified and defined. If the solution to reducing particular bycatch species of concern is not apparent within the boundaries of the simple alterations tested, then more complex modifications (including physical BRDs) warrant examination. Specific designs of BRDs should also be tested to define their limits. For example, if mechanical-sorting grids are required to exclude organisms larger than the targeted species, then a range of configurations that include very narrow and wide bar spacings and small and larger profiles or angles of orientation should be examined (e.g. Broadhurst et al. 2004b). Similarly, because factors like relative water flow strongly influence the performance of BRDs that operate by exploiting differences in the behavior of species (Broadhurst et al. 1999a), these sorts of modifications need to be tested at different positions throughout the gear (e.g. Broadhurst et al. 2002). Coherent hypotheses encompassing the full range of key factors influencing the performance of modifications will facilitate the accurate assessment of the extent to which selectivity might be improved. Quantifying basic, gear-related parameters and their boundaries in terms of reducing bycatch while still maintaining the target catches can save considerable time and effort towards the longer-term development of more selective gears.

In addition to identifying what might be achievable using established technologies, we propose that it is necessary to also consider alternative methods which are not part of the existing conventional gear. That is, examine completely different methods for catching the target species and determine if these have particular attributes that might be used to modify the gear of interest. In the best case, a consideration of alternative methods might provide a completely different fishing gear that could be simply substituted for the problematic gear. But, even in a worst case scenario, comparing alternative methods could highlight specific selection mechanisms that provide new directions for modifying a problematic gear.

This sort of lateral approach is not commonly adopted in studies to improve gear selectivity, although there are numerous examples where key mechanisms associated with one gear have been used to improve the efficiencies of others. One high-profile example involves the use of fire as a visual stimulus (i.e. light) throughout prehistory to augment the catches of simple hooks, spears and clubs (Yami 1976). The benefits of fishing with light were subsequently realized in a plethora of artisanal and industrial fisheries using both static (e.g. gillnets and traps) and active gears (e.g. purse seines) (Yami 1976; Sainsbury 1996). A more recent example is the use of baits to stimulate chemoreception in fish towards traps and longlines being extended to other static gears like gillnets (Engås et al. 2000).

Although not aimed at improving the selectivity or efficiency of particular gears, many other studies have compared alternative and/or competing fishing methods, including longlines vs. gillnets (e.g. Santos et al. 2002; Stergiou et al. 2002; Erzini et al. 2003), longlines vs. trawls (e.g. Hovgård and Riget 1992; Otway et al. 1996; Halliday 2002), longlines vs. trawls vs. gillnets (e.g. Huse et al. 1999; 2000), gillnets vs. trammelnets (e.g. Matsuoka et al. 1990; Acosta and Appeldoorn 1995), gillnets vs. electro fishing (e.g. Colvin 2002), gillnets vs. trap nets (e.g. Hanchin et al. 2002) and gillnets vs. trammelnets vs. seines (Stergiou et al. 1996). In most cases, these comparisons were done to reduce sampling bias and improve resource estimates. An indirect benefit, however, is some information on the relative selection between different gears and methods and the general conclusion that static gears typically are more size- and species-selective than towed gears (e.g. Hovgård and Riget 1992; Løkkeborg and Bjordal 1992; Huse et al. 1999; Stergiou et al. 2002). Despite these, and other known differences among fishing methods and gears, few studies have attempted to use this sort of information to resolve bycatch issues. The potential benefits of such a lateral approach towards improving the selectivity of problematic gears are explored in the following experimental case study comparing towed and static artisanal fishing gears for penaeids in New South Wales (NSW) Australia.

A case study of gear-specific selection for penaeids in estuaries in NSW, Australia

Introduction

Commercial fisheries for penaeids occur throughout rivers and coastal lagoons in NSW, Australia and have a total value of approx. \$A8 M per annum. Catches include 3 species, although school prawns, *Metapenaeus macleayi*, account for more than 90% of the annual production (approx. 925 t). These penaeids are targeted using several types of small-scale fishing gears that include trawls (Figure 1A), seines (Figure 2A) and trap nets (Figure 3A).

Trawls and seines are both towed gears, designed to actively direct organisms along their wings, through a main body and into a collection bag (termed the 'codend'), where most of the size selection is believed to occur (Figures 1 and 2). Penaeid trawls used in NSW estuaries have a head line length less than 11 m and are dragged along in single or multi-rigs behind small vessels (Figure 1C) at approx. 1.2 ms^{-1}. Seines have comparatively longer wings (head line lengths of at least 20 m) than trawls and are set using anchors, buoys and 100-m ropes in a semi-circular configuration around the area to be fished (Figure 2). Immediately after setting, the wings are hauled together and the seine retrieved at a stationary vessel (Figure 2B). In contrast to trawls and seines, trap nets are static gears and catch prawns by exploiting their migratory behavior within estuaries, mostly at night and between the last and first quarter phases of the moon. Trap nets comprise a long (130 m) wall of mesh (like the wing of a trawl or seine) secured between a vertical stanchion located near the shore and the horizontal gunwale of a dory anchored on a lake (Figure 3). The prevailing current causes the netting to assume a parabolic shape, effectively trapping moving prawns and directing them along the wall of netting towards the horizontally-orientated bag (termed 'bunt') at the dory. Fishers facilitate this movement of catch by regularly lifting and hauling sections of the trap net over a dory, so that it passes underneath the trap net and the catch is rolled towards the bunt (Figure 4B).

All trawls, seines and trap nets used to catch penaeids in NSW are managed by a range of gear-specific regulations that include minimum legal-mesh openings throughout of 40, 30 and 25 mm, respectively. Fishers generally target penaeids larger than 15 mm carapace length (CL), but most of the gears retain bycatch that comprises at least some proportion of small, unwanted conspecifics. The selection of these individuals appears to be at least partially gear dependant, with previous studies indicating that, despite having the smallest size of mesh (i.e. 25 mm), trap nets have low bycatches and select relatively large penaeids across a narrow range of sizes (Broadhurst et al. 2004a; 2004c). Our aims in this case study were: (1) to test this hypothesis of gear-specific selection by comparing the selectivity of a trawl, seine and trap net, all rigged with exactly the same size, hanging ratio, twine thickness and material of mesh in the codend or bunt (i.e. collection bag) across similar spatial and temporal scales; and (2) determine if this sort of information can be used to further the development of selective gears.

Methods

This experiment was done on commercial prawn-trawl grounds in Lake Woolooweyah (29^0 26' S, 153^0 22'E) during two weeks in August 2003 using chartered commercial penaeid fishers. All fishing was done over a combination of sandy and mud bottoms in depths ranging from 1 to 3 m and within an area of approx. 5 hectares.

Three commercial fishing gears were used in the study: (1) a Florida Flyer trawl (7.32-m headline) made from 40-mm knotted mesh (1.2-mm diameter – ø, 3-strand twisted polyethylene- PE twine) throughout the wings and body (1N3B taper) and rigged as part of a twin gear configuration (the 'twin' trawl was not used in the study) (Figure 1); (2) a seine (headline length of 20 m) made from 30-mm knotted mesh (the same twine as above) through the wings and body (same taper as above) (Figure 2); and (3) a trap net (headline length and stretched depth of 130 and 6 m, respectively) made from 25-mm knotted mesh (0.4 mm ø, 3-strand twisted polyamide – PA twine) hung at a ratio (E) of 0.5 throughout. An additional trap net (130 x 6 m) was constructed from 9.5-mm PA netting (0.7 mm ø, braided twine) and used as the control for the commercial trap net design above (see Broadhurst et al., 2004c for a detailed description of trap net designs).

Two identical plastic Nordmøre-grids (600 x 400 mm) were installed into the aft bodies of the trawl and seine without guiding panels (see Broadhurst and Kennelly 1996a for details on construction). Zippers (1.45 m in length) were attached immediately posterior to the Nordmøre-grids to facilitate changing codends (Figures 1A and 2A). Two codends were constructed for use with the trawl and seine: a treatment codend made from 25-mm mesh (identical to that used in the commercial trap net) and a control codend made from 9-mm mesh (0.3 mm ø, 3 strand twisted PA) (Figure 1B). Both codends had a stretched length of 1.05 m and were attached to 1.45-m zippers at a hanging ratio of 0.5 (i.e. the same hanging ratio as that used throughout the trap nets). Using the zippers, the two codends could be interchanged on the trawl and seine net bodies (Figures 1A and 2A).

On separate days or nights, each of the three treatment gears described above (i.e. the trawl and seine with the 25-mm codend attached and the 25-mm trap net) were alternately fished with their respective control gears. The trawl and seine were hauled at commercial speeds of 1.2 and 0.13 ms^{-1}, respectively. We attempted 4 replicate, alternate 14-min randomly-located hauls or deployments of each treatment gear and their respective control per day or night. A total of 8 balanced replicates were completed over two days for each of the trawl and seine (between 08:00 and 15:00) and over three nights (between 18:30 and 24:00) for the trap net. With the exception of the common soak time (14 mins), no attempt was made to standardize effort between the gears.

The following categories of data were collected from each replicate deployment: the weight of total school prawns and a subsample (at least 250 prawns from each codend or bunt) of their lengths (to the nearest 1 mm CL); the number of total school prawns and the number and weight of retained school prawns (> 15 mm CL - estimated from the measured subsample); the weights of total bycatch (comprising discarded school prawns and fish) and fish bycatch; and the numbers of all fish.

Non-metric multivariate analyses were used to test the hypothesis of there being no differences in the structures of catches between the 3 treatment gears. Counts for all species were log(x+1) transformed (to enhance the contributions of species caught in low abundances) and used to develop similarity matrices based on the Bray-Curtis similarity measure. Multidimensional relationships among ranks of the similarities from individual deployments of each of the three treatment gears were displayed graphically in a multidimensional scaling (MDS) ordination (Shepard 1962; Clarke 1993). One-way analyses of similarity (ANOSIM) were used to test for differences in catch assemblages between the three gears over their 8 replicate deployments. Similarity percentage (SIMPER) analyses were used to identify those species responsible for discrimination between the treatment gears.

One-factor analyses of variance (ANOVA) was used to test the hypothesis of no differences in the ratios of catches of retained school prawns to key bycatches. Prior to analyses, data were log(x+1) transformed (to account for multiplicatively) and tested for heterocedasticity using Cochran's test. Significant F-ratios were investigated using Student-Newman-Keuls (SNK) multiple comparisons.

Size frequencies of school prawns were combined across all tows for each of the 3 treatment gears and their controls. Because previous studies have demonstrated sigmoid selection for all three gears (Broadhurst et al. 2004a, 2004c), parametric curves (logistic and Richards) were fitted to these data using maximum likelihood and REP corrected for overdispersion arising from between-haul variation (Millar et al. 2004). These fits used the estimated-split SELECT model for trouser trawls (Millar and Walsh 1992) and were implemented using a free R function available from www.stat.auckland.ac.nz/~millar/selectware/code.html. Model fits were assessed by likelihood ratio tests and comparing deviance residuals. Pairwise bivariate Wald statistics (Kotz et al. 1982) were calculated using the estimated parameter vectors of appropriate models to test for differences between the selectivities of the treatment gears.

Results

More than 23 species were recorded in the treatment gears, although 98% of catches comprised 6 species, all smaller than approx. 150 mm total length: school prawns (86.9%), southern herring, *Herklotsichthys castelnaui* (6.4%), Ramsey's perchlet, *Ambassis marianus*, (2.4%) silver biddy, *Gerres subfaciatus* (1.0 %), pink breasted siphon fish, *Siphamia roseigaster* (0.8%) and yellowfin bream, *Acanthopagrus australis* (0.7%). MDS had a stress of 0.12 and 0.20 for the best 3- and 2-dimensional ordinations, respectively (Figure 4). Catch structures were significantly different between gears (ANOSIM Global R = 0.54, $P < 0.01$, pairwise comparisons $P < 0.01$ in all cases; Figure 4). SIMPER analyses showed that of the species comprising bycatch, Ramsey's perchlet, southern herring and pink-breasted siphonfish contributed the most towards distinguishing catches between the gears (Table 1).

The mean ratios of weight of retained school prawns to weights of total bycatch and fish bycatch ranged from 1:2.9 to 1:4 kg and were not significantly different between the treatment gears (Table 2). Similarly, there were no significant differences for the ratios of number of school prawns to numbers of yellowfin bream and Ramsey's perchlet (Table 2). Significant differences were detected for southern herring, with a lower ratio recorded in the seine (1:0.001) compared to the trawl (1:0.21) and trap net (1:0.62) (Table 2).

Similar cohorts of school prawns were retained by the three control gears, particularly in the seine and trawl (Figure 5). Using these data, appropriate parametric selection curves were converged for all three treatment gears, although for the seine, these models were not significantly different from the null model (i.e. no selectivity at $P > 0.05$) and so were not presented (Figure 5A). For the trawl and trap net, there was no significant reduction in deviance associated with using a Richard's curve ($P > 0.05$) and so the simpler logistic model was applied (Figure 5B and C; Table 3). Pairwise bivariate Wald tests detected significant differences in parameter estimates of these curves (χ^2 test, $P < 0.01$) with the trap net selecting school prawns at a significantly greater L_{50} and across a considerably lower SR (Table 3). Figure 4C shows that the parameter estimates for the trap net corresponded to an almost vertical logistic curve (i.e. almost 'knife-edged' selection).

Discussion

The results demonstrate considerable gear-specific differences in selectivity, partly evident by the significant dissimilarity of catches between the treatment gears, but mostly by the size distributions of the targeted school prawns retained. These results clearly delineate the three gears and illustrate the utility of trap netting as a method for selectively harvesting penaeids. Prior to a discussion of the consequences of this sort of information in terms of a lateral approach towards improving the relatively poorly-selective towed gears, some explanation of the mechanisms that contributed towards the observed results is required.

All three gears had significantly different assemblages of catches (Figure 4). Considering the temporal scales involved in the experiment, some of the variations in assemblages between the towed gears and the trap net could be attributed to diurnal fluctuations in the abundances and distributions of the key species across the area fished. But for the seine and trawl, which were used at similar times, these variations are more likely to be related to the gears used, reflecting their different net geometries (e.g. mesh sizes through anterior sections) and operational characteristics (e.g. towing speeds). Despite the different assemblages of catches, apart from a significant reduction in the ratio of numbers of retained school prawns to southern herring in the seine, (compared to the other two gears), the individual proportions of key species or total bycatches retained remained similar among the 3 gears. For the seine and trawl, these similar ratios were probably influenced by the presence of the Nordmøre-grid. This is the most effective BRD available for towed penaeid gears in NSW, mechanically separating all organisms larger than 20 mm in width and previously demonstrated to exclude up to 90% of the total bycatch from trawls used in Lake Woolooweyah, with no significant loss of penaeids (Broadhurst and Kennelly 1996a). Varying quantities of bycatch probably entered both the trawl and seine but, because of the Nordmøre-grid, only some proportion of those very small individuals were retained by both gears. While the numbers of these individuals and/or species varied (contributing to the differences in the assemblages of catches observed above), the total weight of bycatch consistently remained quite low and comparable between the towed gears. In contrast to the seine and trawl, the trap net (which had no BRD) retained all individuals that encountered the gear. The similar ratios of retained school prawns to bycatches between the 'modified' towed gears and the conventional static trap net therefore highlights the inherent selectivity of the latter fishing gear.

The selective characteristics of the trap net are best demonstrated by the sizes of school prawns retained (Figure 5). This gear selected individuals at an L_{50} of 14.63 mm and across a SR of 1.49 mm. Despite having the same size and hanging ratio of mesh in the codend, the trawl selected prawns at an L_{50} 1.2 times lower and across a SR more than 2.5 times larger, while the seine was essentially non-selective (i.e. the 25-mm codend retained the same sizes of individuals as the 9-mm control codend). These considerable differences between gears rigged with the same size of mesh in their codend / bunt can be attributed to their different geometries and methods of operation.

For the trap net, hauling the headline and footrope of the entire gear (i.e. 130 m) over the second dory effectively spread the entire transverse section of the netting (i.e. > 3 m) and maintained maximum mesh openings at an area where the catch was dispersed and being progressively rolled towards the bunt (Figure 3C). By facilitating multiple contacts between all school prawns and the open meshes, this process provided numerous opportunities for selection to occur along the entire gear. In contrast, the probability of prawns encountering open meshes in the seine and trawl was considerably reduced. Unlike the trap net, most of the meshes in the bodies of towed gears were orientated at a shallow angle to the movement of catch, effectively reducing the likelihood of prawns encountering meshes as they moved towards the codend. More importantly, owing to variables such as towing speed, drag, twine diameter and taper of the net body, the meshes throughout these towed gears would have opened at only a small fraction of their overall size (Reeves et al. 1992; Lowery and Robertson 1996; Broadhurst et al. 2000). Therefore, those prawns that did encounter meshes probably had relatively little chance of escaping. This is particularly evident in the seine where we observed that, owing to the slow towing speed (0.13 ms^{-1}), most prawns remained in the wings and net body and only passed into the codend during the final stages of hauling when the gear was lifted onboard. This explains the apparent lack of selection in the codend of this gear (i.e. no difference in selectivity between the 25-mm treatment and 9-mm control codends) and also, given the relatively small mesh size in the body of the seine (compared to the trawl), why few individuals would have been able to escape through the meshes in the body and wings.

This experiment illustrated the potential for static trap nets to harvest penaeids considerably more selectively than either of the towed gears, and especially the seine. This information, along with the identification of gear-specific selection mechanisms, is considered below in discussing a lateral approach towards improving selectivity in problematic fishing gears.

Using the lateral approach

The above case study demonstrated the utility of testing very different fishing gears for providing comparative information on relative selection and more importantly, for identifying key mechanisms that may provide direction for improving selection in problematic gears. Although we did not consider the effort involved in the three different methods, the natural temporal restrictions on penaied trap netting (i.e. typically done at night and usually between the last and first quarter moon phases – Broadhurst et al. 2004c) combined with the relatively labor-intensive operation means that far fewer penaieds would probably be caught by this gear compared to the trawl or seine. However, the small-scale trap-net operation described here could easily be enlarged (e.g. using much longer and / or wider walls of netting) and mechanized (e.g. replacing the hauling crew with net drums) without compromising the mechanisms that contributed towards the observed results. Assuming the catchability of the targeted penaieds is maintained, this type of fishing gear (or a modified version) could replace problematic trawls or seines in some artisanal fisheries.

A less extreme option would be to adapt some of the key processes that contribute towards selection in the trap netting to the towed gears. Specifically, the method of hauling the trap net and maintaining contact between penaieds and areas of netting where the transversal mesh openings are maximized is a vital selective attribute in this gear. It should be possible to emulate this mechanism in towed gears by (1) providing and maintaining sufficient openings in key areas and (2) increasing the probability that penaieds encounter these openings to the level that occurs in trap nets.

The starting point for such modifications in trawls is the codend, since this is where most size selection is believed to occur (e.g. Wileman et al. 1996). Selection in conventional diamond-mesh codends is highly variable and influenced by numerous factors including the hanging ratio and length of netting, size, shape and twine thickness of mesh, towing speed of the trawl and weight of the catch (Reeves et al. 1992; Lowry and Robertson 1996; Broadhurst and Kennelly 1996b; Lök et al. 1997; Dahm et al. 2002). Catches in conventional diamond-mesh codends tend to spread horizontally (Fig. 6A), which effectively masks large areas of mesh in the posterior section and often, owing to the associated drag, closes meshes throughout the anterior extension. One of the simplest ways to reduce variability in the size selection of penaied and other crustacean trawls is to open the meshes in the codend by orientating them on the bar so that they are square shaped (Fig. 6B) (Thorsteinsson 1992; Broadhurst et al. 1999b). By maintaining consistent openings throughout the codend, square mesh specifically addresses the first key selective attribute of the trap net examined in the case study (i.e. providing and maintaining sufficient openings in key areas). The second attribute (i.e. increasing encounter probability) might be achieved by considerably reducing the diameter of square-mesh codends (Fig. 6C). Individuals in a very narrow square-mesh codend would have a shorter distance to travel towards the netting than in conventional codends and therefore a greater probability of randomly encountering openings (Broadhurst et al. 1999b). It might also be possible to increase the frequency of encounters between individuals and open meshes by generating turbulent flow in the codend using strategically-positioned panels or aeration.

For the seine used in the case study, improved selection may be achieved by reducing the net taper and increasing mesh openings in the net body (where most selection apparently occurs) and /or increasing the hauling speed. A steeper body taper could increase the probability of prawns encountering the sides of the seine and so, providing mesh openings are maintained, improve size selection (Broadhurst et al. 2000). A faster hauling speed would augment these modifications and also direct more of the catch into the codend where, like the trawl, selection could be further improved by the changes to codend geometry suggested above.

Improvements to gears, like the trawls and seines examined above, should not only be limited to attempts at mimicking the key attributes of one particular type of inherently selective gear. Instead, it should be possible to identify the attributes of a range of different gears and their methods of operation and examine their utility for increasing selection in problematic gears. For example, another modification that could reduce the bycatch of fish from crustacean trawls and seines involves attaching hydrophones at the mouth of the net. Many artisanal fisheries throughout the world have traditionally used noise, generated during physical disturbances, to herd fish into static gears like gillnets (e. g. Gray et al. 2003). Using the same logic, an appropriate volume and frequency emitted from hydrophones positioned at the otter boards or wings could initiate a response in some fish species that causes them to avoid the mouth of trawls and seines and so improve species selection. These sorts of simple modifications could provide the key to improving selection in problematic gears.

Conclusions

Like the selection mechanisms identified in the case study, solutions to problematic selectivity issues are gear- and fishery-specific. Obviously no single solution will be appropriate for all gears and fishing methods. Fishers and fishing technologists should consider other gears and other fisheries because sometimes, critical solutions to selectivity problems will reside there and not in the particular fishery and gear under examination. We believe that only by fully testing the limits of what is achievable within the confines of the fishing gear under examination and considering selection processes in other gears and how they may be used, can one continue to strive towards ‘perfect selectivity’ in fishing technology. Such a lateral approach should ensure progression towards incrementally more selective fishing gears.

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TABLE 1. Contribution of 99% of species to the similarity matrix of catches in the treatment seine, trawl and trap net.

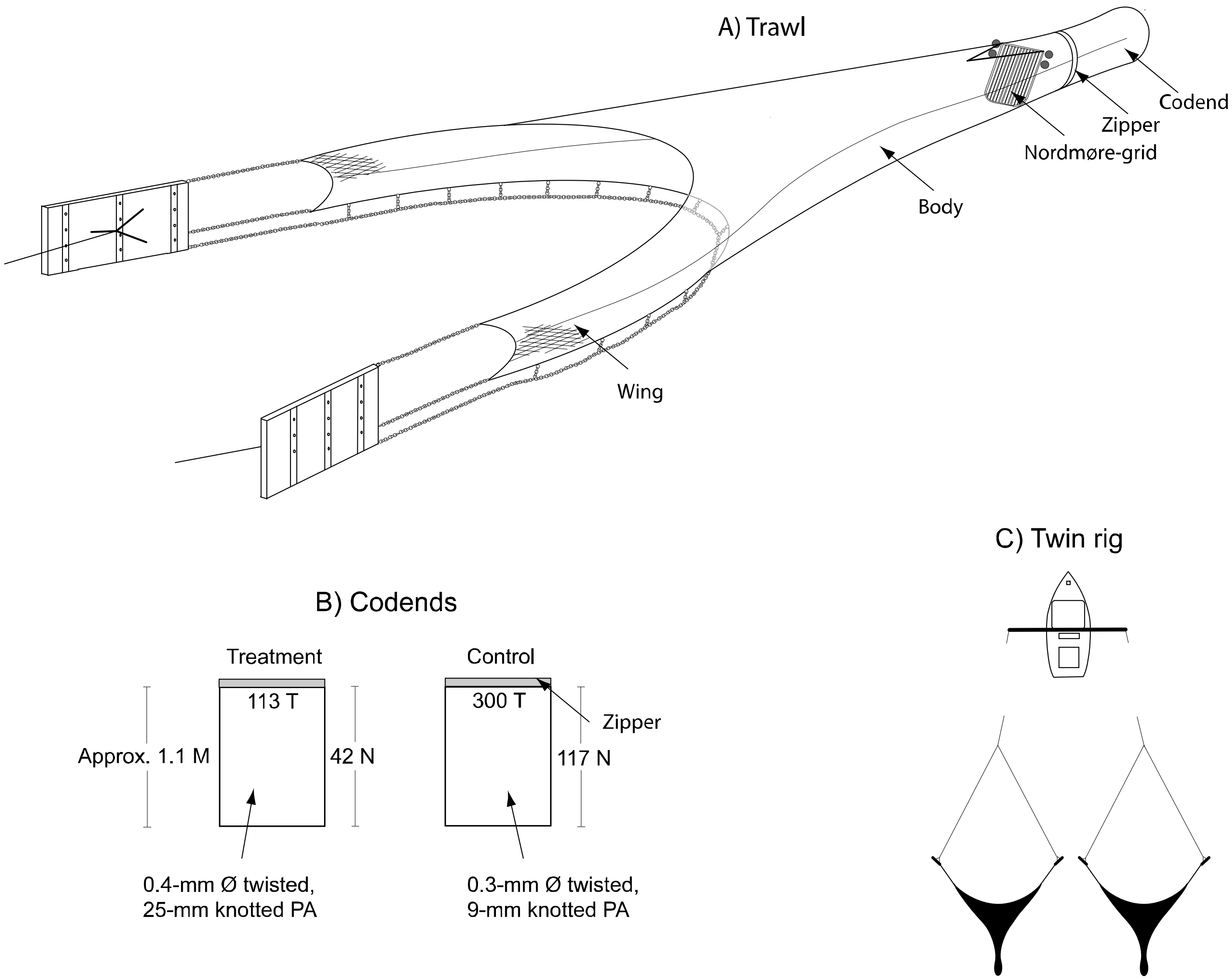
Species	% contribution	Cumulative %
Seine		
School prawn	93.18	93.18
Ramsey's perchlet	4.12	97.31
Silver biddy	1.25	98.56
Yellowfin bream	0.54	99.10
Trawl		
School prawn	81.04	81.04
Southern herring	7.01	88.05
Pink breasted siphon fish	3.15	91.21
Ramsey's perchlet	2.91	94.12
Yellowfin bream	2.52	96.64
Silver biddy	2.14	98.77
Bottle squid	0.63	99.40
Trap net		
School prawn	77.29	77.29
Southern herring	14.99	92.28
Ramsey's perchlet	5.39	97.67
Fantail mullet	0.61	98.28
Yellowfin bream	0.54	98.81

TABLE 2. Mean (± se) ratios of school prawns-to-catch variables, F ratios from the 1-factor ANOVA to determine the effects on these variables due to fishing with the different treatment gears (i.e. the 25-mm trap net and the trawl and seine with the 25-mm codend) and where required, Student-Newman-Keuls tests of means. All data were log(x+1) transformed. *P < 0.05; ns, non significant; na, not applicable.

Ratio	Seine	Trawl	Trap net	F ratio	SNK test
Weight (1 kg prawns):					
Total bycatch	4.00 (2.22)	3.15 (1.09)	3.04 (1.05)	0.06 ns	na
Fish bycatch	3.56 (2.13)	2.73 (1.08)	2.86 (1.01)	0.09 ns	na
Number (1 prawn):					
Yellowfin bream	0.05 (0.04)	0.09 (0.03)	0.02 (0.01)	1.10 ns	na
Southern herring	0.001 (0.001)	0.21 (0.09)	0.62 (0.25)	4.75*	seine < trawl = trap net
Ramsey's perchelet	0.54 (0.45)	0.11 (0.06)	0.14 (0.05)	0.56 ns	na

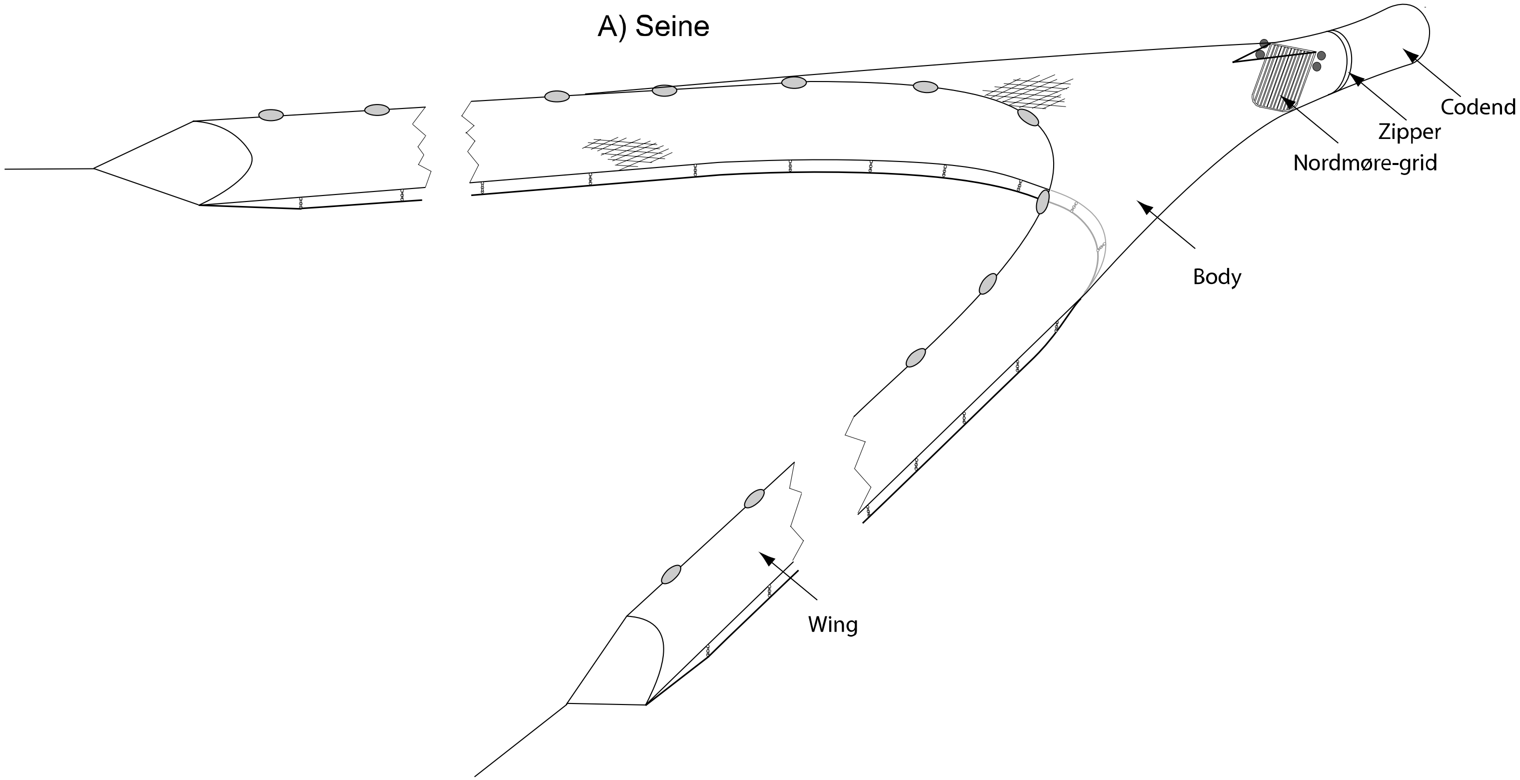
TABLE 3. Carapace lengths at 25, 50 and 75% probability of retention (L_{25}, L_{50}, and $L_{75,}$ respectively), selection ranges (SR) and relative fishing efficiencies (*p*) for school prawns caught by the treatment trawl and trap net (the seine was non-selective at *P* > 0.05).

Parameter	Trawl	Trap net
L_{25}	10.16 (0.70)	13.88 (0.28)
L_{50}	12.02 (0.89)	14.63 (0.37)
L_{75}	13.89 (1.46)	15.38 (0.49)
SR	3.73 (1.12)	1.49 (0.28)
p	0.44 (0.04)	0.75 (1.49)

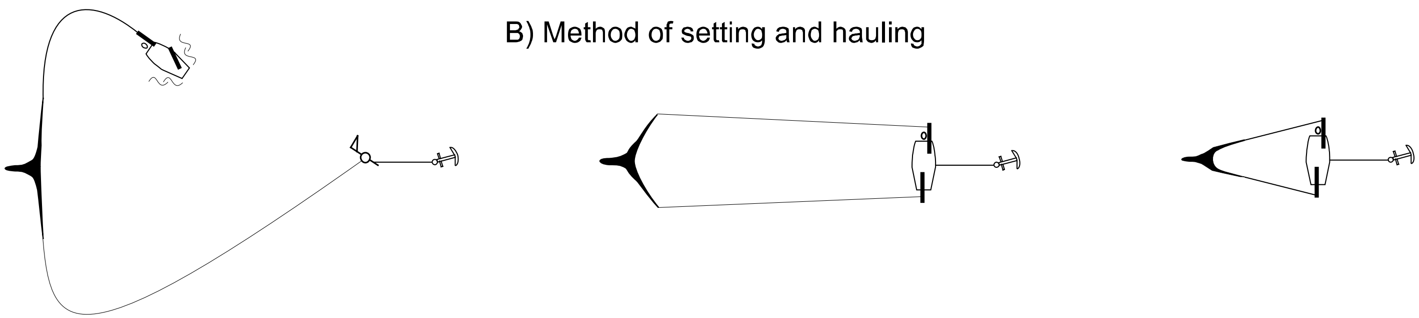


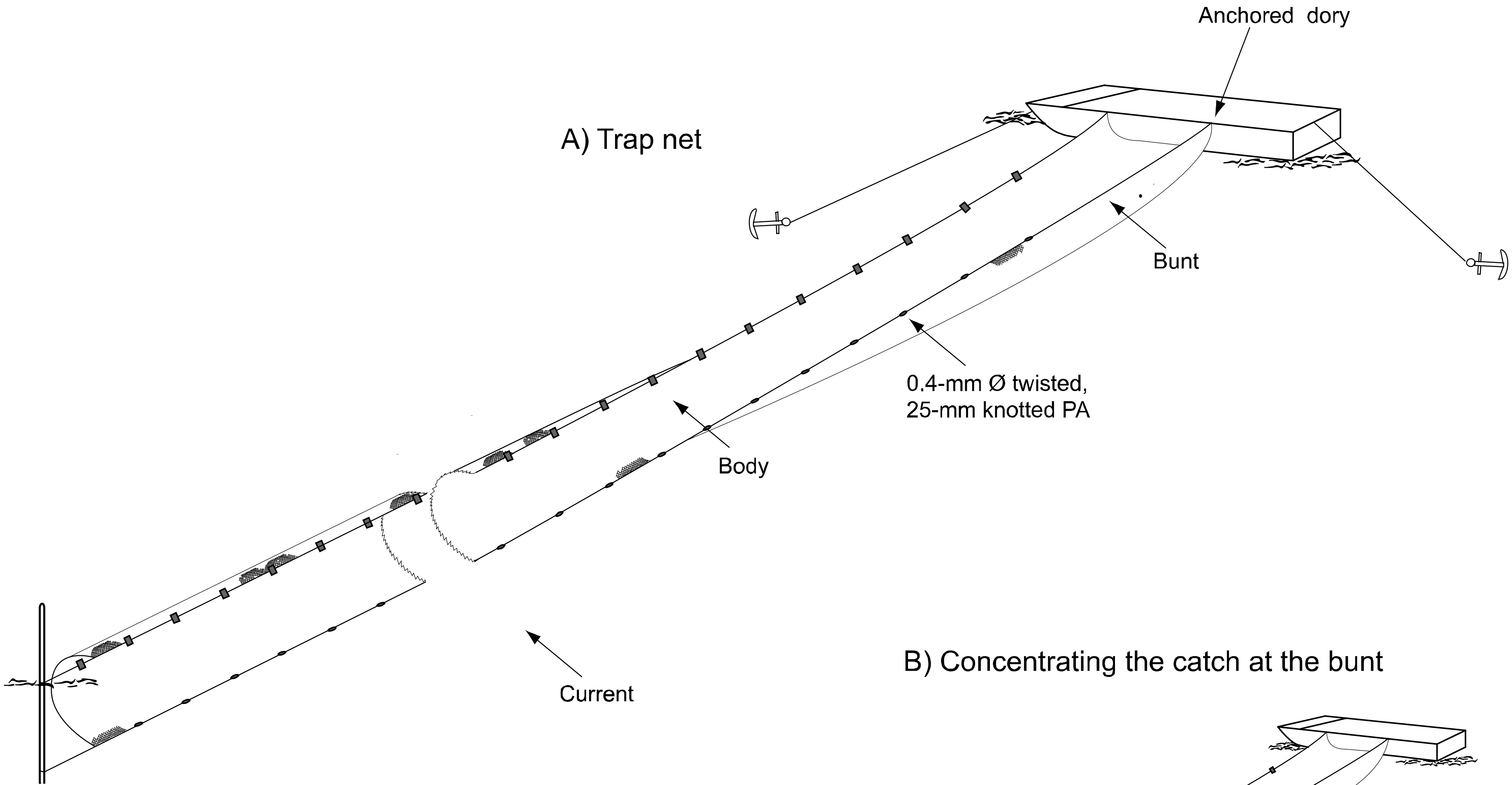
A) Trawl
Codend
Zipper
Nordmøre-grid
Body
Wing
B) Codends
Treatment
Control
113 T
300 T
Zipper
Approx. 1.1 M
42 N
117 N
0.4-mm Ø twisted,
25-mm knotted PA
0.3-mm Ø twisted,
9-mm knotted PA
C) Twin rig

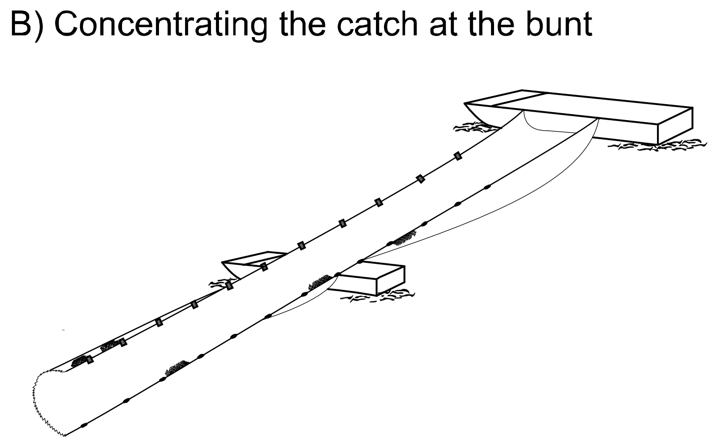
A) Seine



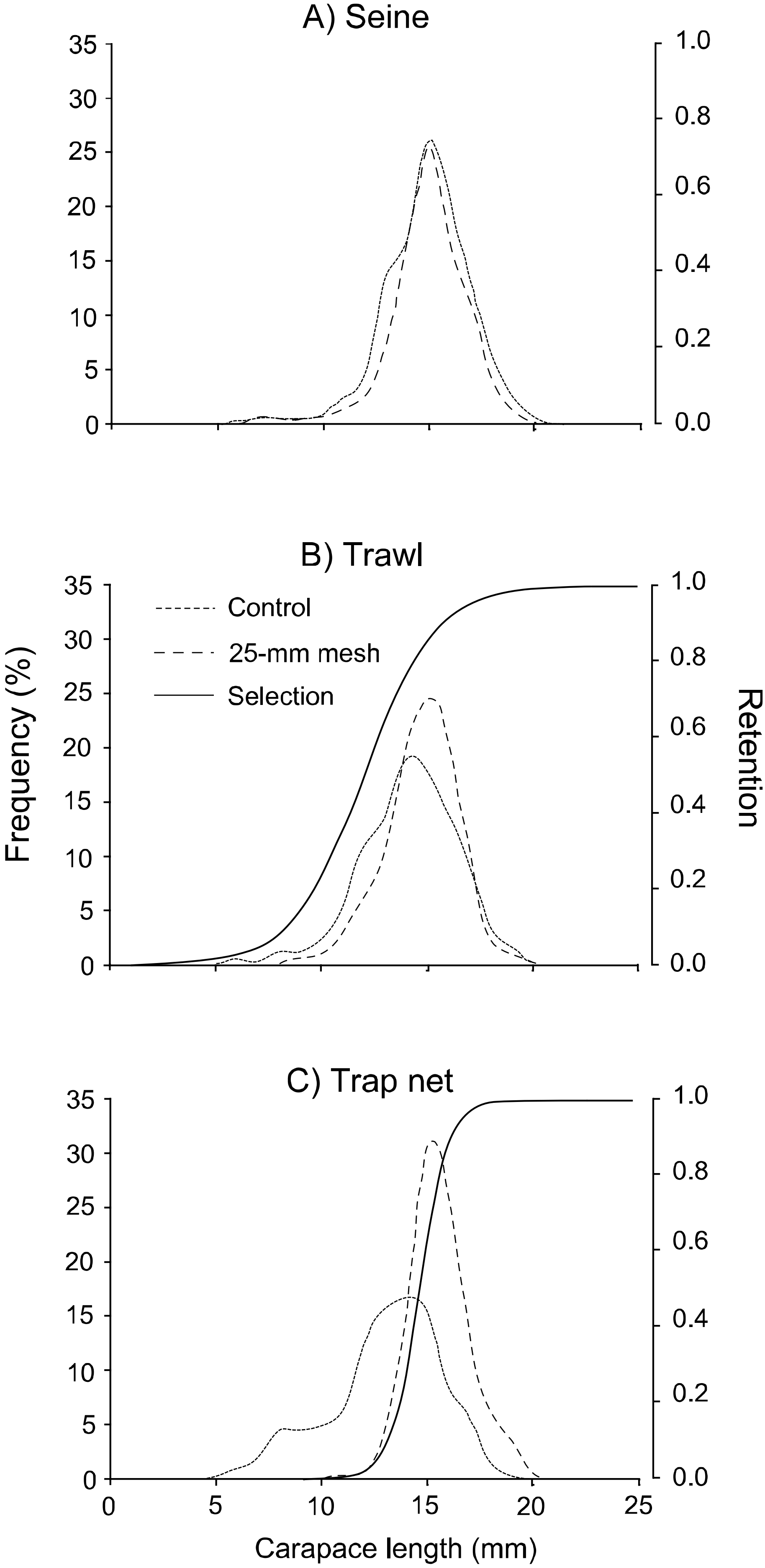
B) Method of setting and hauling

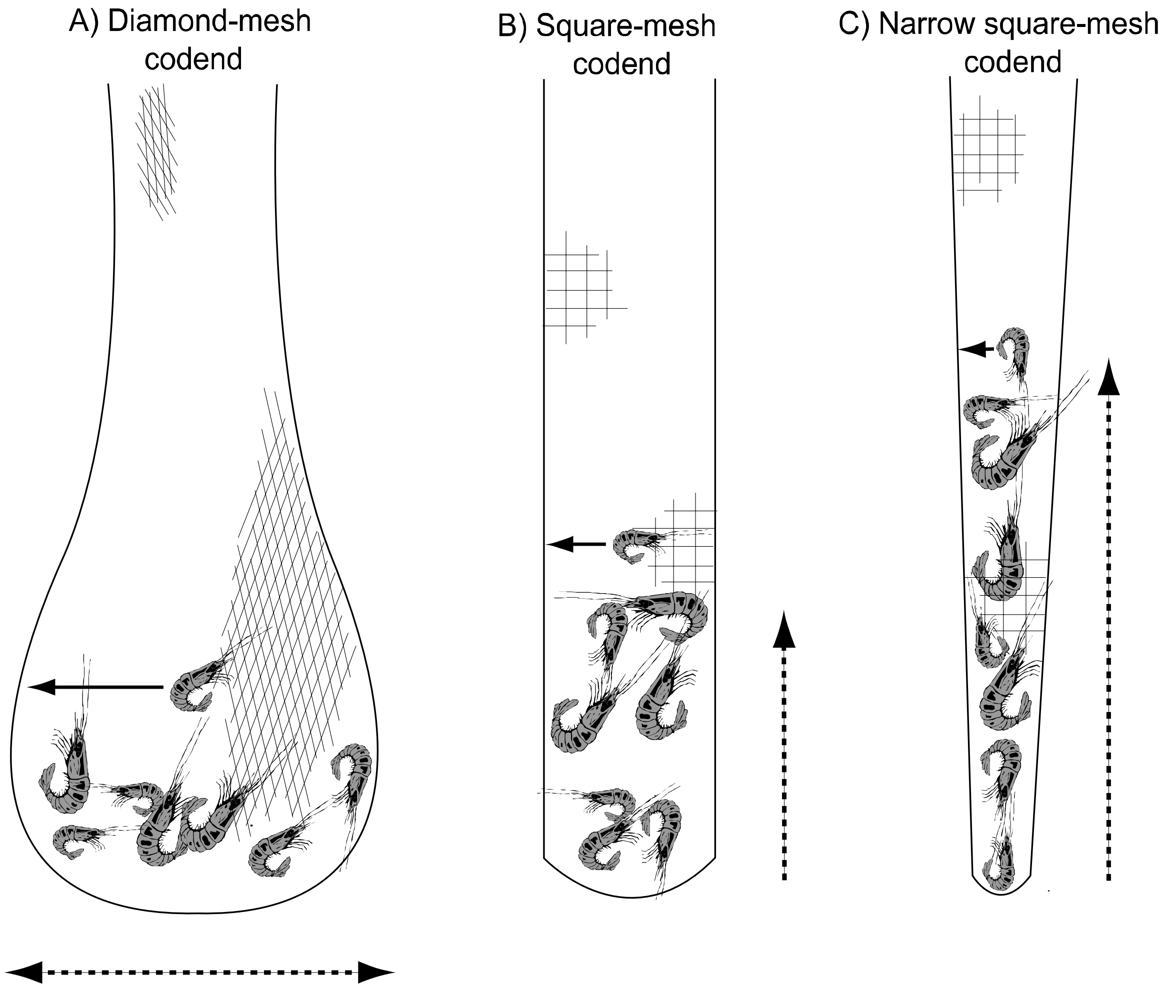



A) Trap net
Anchored dory
Bunt
0.4-mm Ø twisted,
25-mm knotted PA
Body
Current


B) Concentrating the catch at the bunt


Stress = 0.2
Seine ≠ Trawl ≠ Trap net


A) Seine
B) Trawl
C) Trap net
Control
25-mm mesh
Selection
Frequency (%)
Retention
Carapace length (mm)
0
5
10
15
20
25
30
35
0.0
0.2
0.4
0.6
0.8
1.0


A) Diamond-mesh codend
B) Square-mesh codend
C) Narrow square-mesh codend

Appendix 8 - Macbeth, W.G., Broadhurst, M.K. and Millar, R.B. 2005. The utility of square-mesh codends to reduce bycatch in Hawkesbury River prawn trawls. Ecol. Manage. Res. 5(3): 221-224.

fisheries in other estuaries also consider changing to midstream seining as a way to reduce bycatches as well as other potential negative impacts on estuarine ecosystems.

Whilst recent research has shown that incorporating codends constructed of square mesh and grids reduce bycatches in prawn seine nets (Macbeth *et al.* in press), our research has shown that advancements in bycatch reduction are not wholly dependent on technological breakthroughs; simple changes in fishing practice can also have significant impacts on reducing bycatches. Similar simple changes in fishing practice may reduce problematic bycatches in other non-trawl prawn fishing gears.

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13.14

The utility of square mesh to reduce bycatch in Hawkesbury River prawn trawls.

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Key words: *bycatch, penaeid, shrimp, prawn, selectivity, square-mesh codend, trawl.*

Introduction. In New South Wales (NSW), Australia, small (< 10 m) prawn (penaeid) trawlers are permitted to work in areas of Sydney Harbour and the Clarence, Hunter and Hawkesbury River systems. In addition to the targeted species, (mostly School Prawns – *Metapenaeus macleayi*), trawlers also catch and discard large quantities of non-target organisms (termed bycatch) (Kennelly 1993). During the past 15 years, the mortality of juveniles of key species comprising bycatch has raised concerns over the sustainability of stocks. This led to the development of physical modifications, termed bycatch reduction devices (BRDs), that are installed in the bag of the funnel-shaped trawl net where the catch accumulates (i.e. the codend). These BRDs are designed to exclude bycatch organisms similar in size or larger than the targeted prawns, and so improve the size and species selectivity of the trawl net (Broadhurst 2000 for a review). In particular, two BRDs – the Nordmøre-grid (Broadhurst and Kennelly 1996) and the Hawkesbury River square-mesh panel (Broadhurst and Kennelly 1995) – were demonstrated to reduce the catches of juvenile fish by up to 70%, and have subsequently been legislated for use in relevant fisheries.

More recently, efforts have been directed towards further improving the selectivity of trawl nets by reducing the bycatch of individuals smaller than the targeted prawns, and especially prawns considered too small for sale (Broadhurst *et al.* 2004). Specifically, during a recent experiment in the Clarence River, Broadhurst *et al.* (2004) investigated simple modifications to the configuration and size of meshes in the codend, immediately behind the Nordmøre-grid. Compared to conventional codends made from 40-mm diamond-shaped mesh, designs incorporating 20-mm square-shaped mesh hung on the bar (i.e. with a bar length of 10 mm) retained significantly fewer small prawns and fish while maintaining catches of marketable-sized School Prawns. These results were attributed to differences in the geometries of the codends. Unlike diamond meshes, which, irrespective of their size, are characterized by very small lateral openings during fishing (Robertson and Stewart 1988), square-shaped meshes consistently maintain their maximum openings (to the length of the bar), thereby allowing more small organisms to escape without losing marketable catch. Relatively small sizes of mesh hung on the bar in codends can therefore be used to significantly improve the size and species selectivity of trawl nets.

It was concluded that these sorts of square-mesh codends, including designs made from larger sizes of mesh, could augment the selectivity of prawn trawls used in other estuaries. Our aims in this study were to test this hypothesis by comparing the size and species selectivities of codends made from three sizes of square mesh (20-, 25- and 29-mm mesh hung on the bar) with a conventional 40-mm diamond-mesh codend in the Hawkesbury River prawn-trawl fishery.

Materials and methods. The experiment was done using a chartered commercial prawn trawler (10 m) in the Hawkesbury River, NSW (33°34′S, 150°15′E) during May and June 2003. The trawl used was rigged with a zipper that facilitated the removal and attachment of codends and was towed at approx. 1.2 m per second across a combination of muddy and sandy bottoms in depths ranging between approximately 16 and 20 m.

Five codends were constructed: a control and four treatments. All codends were of similar size and had similar anterior sections that included square-mesh panels, as per local regulations (Broadhurst and Kennelly 1995). The posterior section of the first treatment codend, which represented conventionally-used designs (Broadhurst and Kennelly 1995 for details), was made from 40-mm braided and knotted diamond twine (3-mm diameter – ø) and was termed the '40D' codend. The posterior sections of the remaining treatment and control codends were made from knotless 20-, 25-, 29-mm (2.25-mm ø) and 12-mm (1.5-mm ø) polyamide braided twine netting hung on the bar, and termed the '20S', '25S', '29S' and 'control' codends respectively.

The five codends were alternately zippered to the body of the trawl and deployed according to normal commercial operations for 20-min tows. To minimise any potential confounding effects of the fishing order of the codends on each day, they were used in two consecutive randomized blocks, with each block comprising one replicate of each the five codend designs (i.e. a total of 10 tows per day). Over six days we completed a total of 12 replicate tows for each codend.

Following each tow, catches were separated and data collected on the weights and numbers of each species. Where necessary, the total number of School Prawns was estimated by extrapolating a weighed sample of 250 individuals to the total prawn catch weight. The sample of 250 School Prawns (or the entire catch if < 250) and all fish were measured to the nearest 1-mm carapace length (CL) and 5-mm total length (TL), respectively. The presence or absence of Waterweed (*Egeria densa*) was also noted.

The size selectivity for School Prawns was examined by fitting competing logistic and Richard's selection curves using an estimated-split (p) SELECT model (described in Millar and Walsh 1992) to the combined size-frequency data for each codend (Millar *et al.* 2004). Model fits were assessed by chi-squared tests and by visual examination of residual plots. Standard errors (SE) associated with the size-selection parameter estimates of the appropriate model for each treatment codend were REP corrected for over-dispersion arising from between-haul variability (Millar *et al.* 2004). The bivariate form of Wald's *F*-test was used to detect significant differences between the selection curves (Kotz *et al.* 1982).

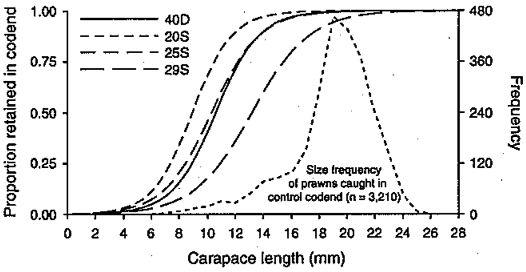

Figure 1. **Logistic selection curves for School Prawns caught in the 40D, 20S, 25S and 29S codends. Size frequency curve is for all School Prawns caught in the control codend.**

Species selectivity was investigated by orthogonal analyses of variance (ANOVA), with 'codends' and 'days' treated as fixed and random factors respectively. Data were $\ln(x + 1)$ transformed so that treatment effects were modeled as (approx.) multiplicative, and then tested for heterocedasticity using Cochran's test prior to ANOVA. Significant *F*-ratios for the main effect of codend were investigated using Student-Newman-Keuls (SNK) multiple comparisons.

Results. School Prawns comprised approximately 68% (by number) of the total combined catch from the four treatment codends (approximately 15 600 individuals). More than 35 bycatch species were recorded, although 76% of the bycatch comprised five fish species: Narrow-banded Sole (*Aseraggodes macleayanus*, 4–15 cm TL), Large-toothed Flounder (*Pseudorhombus arsius*, 2–24 cm TL), Mulloway (*Argyrosomus japonicus*, 2–24 cm TL), Common Stinkfish (*Foetorepus calauropomus*, 3–14 cm TL), and Southern Herring (*Herklotsichthys castelnaui*, 3–14 cm TL). Waterweed was retained in approximately 35% of hauls and occurred in volumes up to approximately 1 m^3.

Size-selection curves were successfully converged for School Prawns for each of the four treatment codends (Fig. 1). In all cases there was no significant reduction in deviance associated with the Richard's model and so the simpler logistic model was applied. The REPs and relative fishing parameters for the treatment codends ranged between 1.39 and 1.69, and 0.52 and 0.55 respectively. The selection curves for the 40D, 20S and 25S codends had CLs at 50% retention – L_{50}s – (± SE) of 10.59 (0.57), 8.90 (0.81) and 10.26 (0.65), and selection ranges – SRs – (± SE) of 3.42 (1.10), 3.12 (1.66) and 3.78 (1.33) respectively, and were not significantly different from each other (Wald tests, $P > 0.05$; Fig. 1). The 29S codend had a selection curve with an L_{50} and SR of 13.16 (0.53) and 4.55 (0.95) respectively, and was significantly different to all other treatment codends (Wald tests, $P < 0.01$; Fig. 1).

The compositions of catches varied considerably among the treatment codends (Table 1). ANOVA detected significant differences for the main effect of codends for the numbers of bycatch species, Narrow-banded Sole and Southern Herring ($P < 0.05$), although SNK tests could not provide a definitive order for these differences ($P > 0.05$). While no other main effects of codends or interactions between codends and days were detected (ANOVA, $P > 0.05$), there were three major trends in the data. First, there

Table 1. Mean catch per tow (± SE) for the four treatment codends used during the experiment (*n* = 12). Data are for selected catch variables of interest and the five most numerically dominant species comprising bycatch. Weights are in kilograms.

Catch variable	Codend			
	40D	20S	25S	29S
Weight of School Prawns	1.97 (0.45)	1.81 (0.15)	1.77 (0.21)	1.69 (0.23)
Weight of bycatch	2.04 (0.28)	1.72 (0.22)	2.19 (0.36)	2.33 (0.53)
No. bycatch species	11.58 (0.53)	10.58 (0.40)	9.75 (0.70)	9.08 (0.51)
No. bycatch individuals	97.33 (11.63)	95.50 (12.49)	113.50 (20.49)	86.92 (18.51)
No. Narrow-banded Sole	17.50 (6.84)	25.33 (6.93)	38.67 (12.52)	37.00 (11.93)
No. Large-toothed Flounder	22.33 (4.61)	20.42 (4.23)	24.67 (4.62)	24.42 (4.21)
No. Mulloway (<13 mm TL)	2.83 (1.15)	3.92 (2.06)	2.50 (0.96)	0.58 (0.26)
No. Mulloway (>13 mm TL)	10.17 (1.83)	9.17 (2.44)	5.58 (1.44)	7.50 (2.57)
No. Common Stinkfish	8.58 (2.31)	10.58 (3.57)	12.92 (6.18)	6.25 (1.90)
No. Southern Herring	7.33 (3.22)	7.93 (3.12)	13.67 (7.39)	0.83 (0.41)

were progressively fewer species comprising bycatches from the 40D to the 20S, 25S and 29S codends (Table 1). Second, the 29S codend retained notably fewer small Mulloway (i.e. ≤13-cm TL) and Southern Herring than the other codends, and third, the 25S and 29S codends retained greater mean numbers of Narrow-banded Sole than did the 40D and 20S codends (Table 1).

Discussion. While all three square-mesh codends maintained catches of School Prawns, only the 29S codend significantly improved their size selection (compared to the conventional 40D codend). This result conflicts with observations made in the Clarence River, where the 20-mm square mesh codend selected School Prawns at a significantly greater L_{50} and across a narrower SR than the conventional 40-mm diamond-mesh codends (Broadhurst *et al.* 2004). The lack of any significant differences in size selection between the 40D and the 20 and 25S codends in the present study may be attributed to the apparent paucity of small School Prawns (comprising sizes within the estimated SRs of these codends) in the areas fished (Macbeth *et al.* 2005). Further, the presence of Waterweed and the masking effect that this has on meshes may have also had an influence on selectivity. Large volumes of Waterweed were observed to accumulate immediately in front of the catch in the codends, blocking many of the square meshes and limiting the escape of those few small (7–12 mm CL) School Prawns that entered the codends. The square meshes in the 29S codend may have been sufficiently large for the Waterweed to have less influence on selection, although the comparatively wide SR for this codend indicates that this was still quite variable.

While there were no significant differences in the total numbers and weights of bycatch retained among the treatment codends, the square-mesh designs, and particularly the 29S codend, retained different sizes and types of fish than the 40D codend. For example, fewer small, fusiform or laterally-compressed fish ≤ 13-cm TL, such as juvenile Mulloway (a commercially and recreationally important species) and Southern Herring, were retained in the 29S codend than in the 40D codend. Conversely, the 29S codend retained almost twice as many Narrow-banded Sole (a dorsally compressed fish) than the 40D codend. These observations can be attributed to the morphology of these fish in relation to the size and configuration of meshes. Most small Mulloway (< 13 cm TL) would have been sufficiently narrow to escape through the 29-mm square meshes. In contrast, even small individuals of dorsally compressed species like Narrow-banded Sole were wider than the 14.5-mm bars in the 29S codend. Although the lateral mesh openings in the 40D codend were probably very narrow during fishing, some small narrow-banded sole may have been able to actively force their way through owing to the diagonal mesh openings being close to their maximum size (i.e. 40 mm). Similar results have also been reported in other studies (e.g. Petrakis and Stergiou 1997). Regardless of the mechanisms that contributed to the above observation, the 29S codend retained approximately 22% fewer bycatch species than the 40D codend, which suggests an overall improvement in species selectivity, despite the variability of the catches.

The results from this experiment support the conclusion by Broadhurst *et al.* (2004) that square-mesh codends have the potential to improve the size selectivity of prawn-trawl nets in NSW estuaries. Although the compositions of the bycatches for the various treatment codends used during the experiment were quite variable, preventing definitive assessments regarding species selectivity, there is sufficient evidence to justify further examination of codends made from 29-mm square mesh in the Hawkesbury River. But, given the problems associated with meshes being masked, such codends would probably be even more effective with the concomitant development of some sort of BRD that ejects Waterweed. Such gear-based modifications that improve the selectivity of trawls would be a positive step towards minimising the environmental impacts while maximising the sustainability of these fisheries.

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13.16

FROM: Buckley, R. (ed.) (2004) *Tourism in Parks: Australian Initiatives.* International Centre for Ecotourism Research Griffith University, Queensland Australia.

13.16.1

Political history of tourism and conservation in Australia. pp. 22–30. John Brown, Chairman, Tourism Task Force (Level 1, 80 Williams St, Sydney NSW 2000, Australia).

Key words: *ecotourism, managing impacts, nature tourism, preidcted growth.*

Tourism has played a significant political role in helping protect Australia's natural environment. Just a few of the many examples include the rivers of southern Tasmania in the early 1980s, the rainforest of north Queensland in the late 1980s, the forests of south-western Western Australia in 2001, and currently the cool termperate rainforests of Tasmania. Mistakes have been made, such as the role of the 'white-shoe' tourism development and urbanisation of Australia's eastern coastline. There are challenges for the future. By 2010 we expect twice as many international visitors to Australia. Our tourism infrastructure, particularly for nature tourisms and regional areas, is not equipped to handle that increase. We have a major task to maintain Australia's 'clean and green' destination image. For many years the ecotourisms and nature-based industries have developed and applied best-practice models of operation in relation to ecologcial and cultural factors. It is time now that the tourism industry's major corporations move further to take on board the work pioneered by this sector and improve their environmental management.

13.16.2

Principles for managing commercial tour operators in Australia's protected areas. pp. 73–78. Rod Hillman, Chair, Tourism in Australia's Protected Areas Forum and member of TAPAF Environment ACT (P.O. Box 144 Lyneham, ACT 2602, Australia).

Key words: *licencing, managing impacts, national standards, nature tourism.*

The Tourism in Australia's Protected Areas Forum, TAPAF, is an informal information-sharing collaboration between representatives of proteced-area management agencies and tourism agencies across Australia. TAPAF has compiled a set of national principles for managing commercial tour operators (CTO) in protected areas. These are needed to address the many disparities between jurisdictions which create unnecessary complications for CTO. The principles recognise that CTO are an integral component of the total visitor use in protected areas, but that the agencies have overriding responsibilities for conservation and various social constraints. The principles aim to simplify and harmonise existing licencing systems, terminologies, fees and charges, and performance requirements across Australia. They are gradually being adopted by the various agencies involved.

13.16.3

Managing tourism in the Great Barrier Reef Marine Park – doing it better. pp. 91–98. Virginia Chadwick, Chair, Great Barrier Reef Marine Park Authority (P.O. Box 1379, Townsville, Qld 4810, Australia).

Key words: *biodiversity conservation, ecotourism, managing impacts, nature tourism, planning.*

Significant growth in tourism to the Great Barrier Reef (GBR) in the 1980s and 1990s has presented new challenges for managers. The Wold Heritage listed GBR estends over 2000 km along the Queensland coast of Australia, with 3000 reefs and 900 islands. The world's largest marine protected area, it supports a diverse population of: coral, sponges, molluscs, marine plants and over 15 000 species of fish, one of the world's most important dugong populations and six of the world's seven species of marine turtle, and is a breeding ground for humpback whales. As such, it is an icon for nature tourism and, since the inception of the Great Barrier Reef Marine Park Authority in 1975, a range of tourism management tools have been established in conjunction with the Queensland Government. These include regulatory Zoning Plans, Area Plans of Management and site specific plans, implemented through a standardised permit system, and monitoring and enforcement strategies. Industry best-practice is encouraged and an education and training program is in place. The development of these management tools has been cumulative, responding to issues that have arisen over the past 25 years. The Authority's Tourism and Recreation Reef Advisory Committee is currently examining the existing management arrangements with the view to developing a new, integrated framework which is purpose-built to deliver and improve cost-effective and equitable systems for management of sustainable tourism and recreation use of the Marine Park. This paper reviews the evolution of the management of tourism and recreation in the Great Barrier Reef Marine Park and outlines a way forward which is contemprorary and builds on genuine partnerships between the tourism industry and governments.

13.16.4

Resource and visitor management in NSW National Parks. pp. 132–149. Brian Gilligan and Claire Allen, Strategic Policy Division, NSW National Parks and Wildlife Serives (P.O. Box 1967, Hurstvilled, NSW 2220, Australia).

Key words: *forward planning, funding options, nature tourism, partneships, research needs.*

Protected area managers worldwide face the callenge of conserving natural and cultural heritage, ensuring conservation values are not degraded by the current generation's use and appreciation of these areas. The NPWS manages over 500 parks which receive more than 20 million visits per year, and is facing a number of immediate issues in managing tourism and visitor use. These issues include: the need for monitoring and research; demonstraing the benefits of protected areas to rural and

Appendix 9 - Macbeth, W.G., Broadhurst, M.K. and Millar, R.B. 2004. Fishery-specific differences in the size selectivity and catch of diamond- and square-mesh codends in two Australian penaied seines. Sub. to. Fish. Man. Ecol.

Fishery-specific differences in the size selectivity and catch of diamond- and square-mesh codends in two Australian penaeid seines

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Abstract
Two experiments were done to compare the selectivities and catch compositions of conventional 30-mm diamond-mesh codends and a new square-mesh design made from 20-mm mesh hung on the bar for river and lagoon penaeid seines in southeastern Australia. Compared to conventional codends, the square-mesh design significantly improved the selectivities of the river seine for school prawns, *Metapenaeus macleayi* (Haswell), and the lagoon seine for greasyback prawns, *Metapenaeus bennettae* (Racek & Dall), by increasing their carapace length at 50% probability of retention (L_{50}) and by decreasing the between-haul variability in selectivity. The presence of weed reduced the L_{50} for greasyback prawns caught in the conventional diamond-mesh codend during the lagoon-seine experiment. Differences among codend performances between the seines are discussed in terms of their methods of operation and composition of catches. These differences highlight the need to develop and manage modifications to improve the selectivity of fishing gears on a fishery-specific basis.

Introduction

The capture and mortality of non-target organisms (termed 'bycatch' – sensu Saila 1983) during commercial fishing has raised considerable concerns over the last two decades and resulted in extensive efforts to improve the selectivity of problematic gears for the targeted organisms (Kennelly & Broadhurst 2002). Owing to their small diamond-shaped meshes and active method of operation throughout areas typically characterized by large abundances of small organisms, penaeid (shrimp or prawn) trawls have received the majority of attention (for reviews see Andrew & Pepperell 1992; Alverson, Freeberg, Murawski & Pope 1994; Broadhurst 2000). Numerous studies have been done to test the utility of alterations to the sizes and/or shapes of mesh used in trawls as well as physical modifications specifically designed to exclude unwanted catches (termed 'bycatch reduction devices' – BRDs – see Broadhurst 2000 for a review). Considerably less work has been done with other types of towed penaeid-catching gears such as seines, despite their wide-scale use in many of the same areas as trawls throughout the world's temperate and tropical penaeid fisheries (e.g. Vendeville 1990; Alverson *et al.* 1994).

In the Australian state of New South Wales (NSW), seining for penaeids involves the use of similar gears (all with a minimum legal mesh size of 30 mm), which are operated slightly differently so as to target mostly (i) school prawns, *Metapenaeus macleayi* (Haswell) in rivers, or (ii) greasyback prawns, *Metapenaeus bennettae* (Racek & Dall), and eastern king prawns, *Penaeus plebijus* (Hess), in coastal lagoons. These different estuarine systems and their associated ecologies, combined with the large geographic range of the fishery means that there is considerable spatial and temporal variation in the compositions and abundances of catches (Gray 2001; Gray, Kennelly & Hodgson 2003). One common problem, however, is the bycatch of many organisms smaller than the targeted penaeids, and especially conspecifics considered too small for sale (i.e. < 15-mm carapace length – CL; Macbeth, Pollard, Steffe, Morris & Miller 2002). Despite evidence to suggest that the 30-mm mesh used throughout penaeid seines in NSW is inappropriate (Broadhurst, Millar, Kennelly, Macbeth, Young & Gray 2004), no formal studies have been done to determine selectivity or the extent to which this might be improved.

One of the simplest strategies for improving the selectivity of towed gears is to orientate the codend meshes so that they are square shaped (e.g. Thorsteinsson 1992; Tokaç, Lök, Tosunoglu, Metin & Ferro 1998; Broadhurst, Larsen, Kennelly & McShane 1999; Broadhurst *et al.* 2004). Unlike diamond-shaped meshes in codends, which tend to have variable lateral openings typically < 25% of the stretched inside-mesh length (SIML – Ferro & Xu 1996), square-shaped meshes maintain their maximum openings (i.e. at 50% of SIML) during fishing (MacLennan 1992). This means that relatively small square mesh (e.g. SIML up to half that of the existing conventional diamond mesh) can significantly improve selectivity. The utility of square-mesh codends has already been demonstrated for other penaeid-catching gears, although with some variability. For example, Broadhurst *et al.* (2004) and Macbeth, Broadhurst & Millar (2005) showed that compared to conventional diamond-mesh trawl and stow-net codends (SIMLs of 40 and 30 mm, respectively), a codend made from 20-mm knotless mesh hung on the bar selected school prawns at greater CLs at 50% probability of retention (L_{50} – e.g. increase from 8.6 to10.3 mm and from 8.5 to 9.7 mm, respectively), with similar or smaller selection ranges (SR – e.g. reductions from 3.9 to 3.5 mm and from 3.6 to 2.6 mm, respectively).

Our aim in the present study was to quantify and compare the selectivities and catch components of conventional diamond-mesh codends and a new square-mesh design in two distinct estuarine penaeid-seine fisheries: a river and lagoon fishery targeting school and greasyback prawns, respectively, via selectivity experiments involving replicate hauls performed under commercial conditions. Considerable, and often extreme, between-haul variation in selectivity can occur under replicate deployments of a fishing gear (Fryer 1991), with spurious inference resulting if this variability is not considered in the analysis of selectivity data. Some of this variability may be due to measurable covariates, such as catch size (e.g. Campos, Fonseca & Erzini 2002; 2003), and amount of debris accumulated in the codend (Polet 2000). Therefore, two contrasting methods of estimating selectivity were used, with one also able to quantify the influence of explanatory variables (such as catch size and presence/absence of debris) that may account for between-haul variability.

Materials and methods

Two separate experiments were done in the Richmond River (28o 53' S, 153o 35' E) and Smiths Lake (32^o 23' S, 152^o 29' E), NSW using commercial river and lagoon seines, respectively. The seines had similar bodies and were both made entirely from 30-mm knotted polyethylene (PE) netting (approx. 1.2 mm diameter – ø, 3-strand twisted twine). The river seine had a wing depth of 130 normals (N), a buoyed 40-m headline and a 35-m footrope attached to a weighted leadline by 100-mm chain drops. Hauling ropes (130-m; 8-mm ø, 3-strand twisted PE) were attached to a bridle at each wing end. The lagoon seine had a wing depth of 100 N, a headline and footrope both measuring 140 m, separated at each wing end by timber spreader bars attached to 100-m hauling ropes (10-mm ø, 3-strand twisted PE). Both seines had zippers (Buraschi S146R, 1.1 m in length) attached at the posterior end of their bodies to facilitate changing the codends. The lengths of these zippers were based on the expected fishing circumference of the majority of conventional codends, which was calculated as the estimated fractional mesh opening (0.35) x the circumference in meshes x the mesh size (Broadhurst et al. 1999).

Five codends were constructed: three treatments and two controls. All codends were made from dark netting and had a total length and fishing circumference of 3 and 1.1 m, respectively. Zippers (see above) were attached to the anterior sections of these codends and a 1.1 m length of 5-mm chain sewn to the end of the posterior sections, as per normal commercial operations. Commercial fishers suggested that the drag created by this chain helps to prevent the codends from fouling during deployment. The first and second treatment codends, termed the 100- and 150-diamond codends, represented normal commercial diamond-mesh designs and were made entirely of the same 30-mm knotted PE netting (1.4-mm ø, 3-strand twisted twine), but had circumferences of 100 and 150 meshes, respectively (Fig. 1A & B). The third treatment codend was made entirely of 20-mm knotless polyamide-PA netting (2.5-mm ø braided twine) hung on the bar (i.e. square-shaped mesh with a bar length of 10 mm) and was termed the 20-mm square codend (Fig. 1C). The two controls were termed the diamond- and square-control codends and were made entirely of 16- and 12-mm knotless PA netting (1.5-mm ø braided twine) that was hung on the diamond and bar, respectively (Fig. 1D & E).

All diamond-mesh codends were made from a continuous section of netting and rigged with traditional draw strings to facilitate the removal of catch (Fig. 1A, B & D). In contrast, the two square-mesh codends were constructed in two sections; comprising upper and lower panels sewn together with opposite knot directions (see Broadhurst *et al.* 1999 for details). Appropriate-sized circular panels of square-shaped mesh were attached to their posterior ends and, instead of a conventional drawstring, zippers (Buraschi S146R, 0.3 m in length) were sewn into each of the lateral seams to allow removal of the catch. Broadhurst *et al.* (2004) hypothesised that these circular panels of mesh would improve the encounter probability of organisms and therefore the selectivity of the codends.

Experiment 1 - River seining

Experiment 1 was done over two periods (each comprising five days) during appropriate tides in September and October 2002. Each replicate haul involved the fisher securing a buoyline and buoy (to a tree or submersed anchor) upcurrent from the area to be fished. One of the 100-m hauling ropes was attached to the buoy and the entire hauling rope-seine configuration deployed from a dory in an arc around the fishing area. The fisher returned to the buoy, securing the dory to it and then retrieved the two hauling ropes (guided by gantries) at a velocity of approx. 0.5 ms^{-1} using a small, motorized winch. The seine was then hand-hauled into the dory and the codend emptied. The entire process took approx. 15 minutes.

All five of the codends were alternately zippered to the body of the river seine and fished according to the method described above. To minimise any potential confounding effects, the testing order of codends was randomised in three blocks (each block comprising one replicate haul of the five codends) on each day. Over 10 days, we completed a total of 30 replicate hauls for each codend (i.e. 2 periods x 5 days/period^{-1} x 3 replicates/day^{-1}).

Experiment 2 – lagoon seining
Experiment 2 was done at night between the last quarter and new moon phases in November and December 2002. Each replicate haul involved the fisher securing a buoy to the end of one hauling rope and deploying it, along with the hauling rope-seine configuration, over the stern of a dory and around the area to be fished. The dory then returned to the buoy and towed the entire seine configuration for 10 minutes at a speed of 0.5 ms^{-1} until the two 70-m wings of the seine came together. A second buoy was secured to the end of the second hauling rope and it was towed and repositioned so that the wings of the seine were stretched apart. The fisher then retrieved the first buoy, dragging it in an arc back to the second buoy. The entire seine configuration was then towed for another10 minutes as per above. At the end of this second tow, the codend was hauled onboard and emptied.

The above procedure took approx. three times longer than that required to perform a single haul of the river seine. Consequently, there was insufficient time within nights to adequately replicate all five of the codends examined during experiment 1. Based on the results of this earlier work (see Results section), we selected only the 100-diamond, 20-mm square and square-control codends for testing during experiment 2. These three codends were alternately zippered to the body of the seine and used in two randomized blocks during each of nine nights, providing a total of 18 replicates for each codend.

Data collected
After each replicate haul, the contents of the codend were separated onboard the dories. The following categories of data (where applicable) were collected: the weight and number of each species of prawn or fish (where necessary, the number of the target species was estimated by scaling up a weighed sample of 250 individuals). In addition, the carapace lengths (CL) of all prawns in this sample (or entire catch if less than 250) and all other penaeids were measured, along with the total lengths of all fish, to the nearest mm. The presence or absence of weed and jellyfish was also noted, but not recorded as bycatch.

Analyses of size selectivity
Two methods for accounting for between-haul variability in size selectivity were employed. The first performs a combined-hauls analysis, but does so by using a simultaneous fit to the (scaled-up, where appropriate) data from each individual haul. This enables overdispersion in the data to be quantified using a replication estimate of dispersion (REP). This overdispersion includes the effects of between-haul variability and of the scaling-up of the length frequency data for catches that were subsampled (Millar, Broadhurst & Macbeth 2004). These combined-hauls analyses give selectivity parameter estimates and standard errors that are appropriate to the overall selectivity of a hypothetical fishery that consists of further replicate deployments of the gears, and is implicitly averaging out the between-haul variation. Here, the overall-selectivity curves of different mesh configurations were compared using the bivariate form of Wald’s F-test (Kotz, Johnson & Reid 1982).

The second approach uses the hierarchical mixed-effects model formulated by Fryer (1991), but employs a new way of fitting this model (Millar et al. 2004). The approach of Fryer (1991) fits a linear mixed-effects model to selectivity parameter estimates from individual fits to the data and is therefore crucially dependent on good distributional properties of the individual estimates. In contrast, Millar et al. (2004) uses recently developed generalized linear mixed model software to obtain an exact maximum likelihood fit to the (unscaled) data from each haul. This mixed-effects model approach is more formal and permits explanatory variables (catch size and presence/absence of debris) to be formally included and provides rigorous statistical inference via likelihood ratio tests.

Logistic and Richard's selection curves were fitted via both methods using an estimated-split (p) SELECT model (Millar and Walsh 1992; Millar et al. 2004) to allow for unequal density of individuals entering the experimental and control gears. The REP estimate of Millar et al. (2004) estimates a split parameter (p) for each individual haul. The mixed-effects model allows p to vary randomly between hauls by assuming that q=logit(p) is normally distributed with mean μ_q and variance σ^2_q.

Analyses of catch components
The weights and/or numbers of total penaeids, each penaeid species, total bycatch, and the numbers of bycatch species were analysed using appropriate analyses of variance (ANOVA). Data were ln(x+1) transformed (to model treatment effects as approx. multiplicative) and tested for heterocedasticity using Cochran's test. Data sets showing significant heterocedasticity were analysed at a significance level of P = 0.01 in the ANOVA to counteract the increased probability of type I error (Underwood 1981). In all analyses, where interaction terms were non-significant at P > 0.25, pooling with the residual was done to increase the power of the test for the main effect of codends. Significant F ratios were investigated using the relevant a priori planned comparisons.

Results
Experiment 1: river seining
School prawns were the only penaeids captured during experiment 1 and comprised approx. 97% (by number) of the total catch, with an additional 20 bycatch species also recorded. The catch weight of school prawns varied substantially during the experiment, and within each replicate sampling block. For example, over all hauls, the smallest school prawn catch was just 0.2 kg and the largest 34.8 kg (both being 150-diamond codend catches), and within block 20 the catch varied from 0.2 kg (150-diamond codend) to 34.2 kg (20-mm square codend).

Analyses of size selectivity
For the combined-hauls analyses (via a simultaneous fit to individual-haul data), parametric selection models were successfully fitted to school prawn data for all of the treatment codends using each control codend. Fits were also obtained for narrow-banded sole, Aseraggodes macleayanus (Ramsay), a dorsally compressed fish, for the 100-diamond and 20-mm square codends using the diamond-control codend, and for the 150-diamond codend using the square-control codend. In all cases, there was no significant reduction in deviance associated with using a Richards curve and because residuals from the simpler logistic fit showed no serious problems, it was used throughout (Fig. 2A; Table 1).

For each of the three treatment codends, there was no significant difference between the school prawn selection curves derived using the diamond- and square-control codends (Wald's tests, P > 0.05; Table 1). However, while the selectivity of the square-control codend could be modelled with the diamond-control as its control (L_{50} and SR of 4.44 and 2.52 mm, respectively - Table 1), the reciprocal model failed to converge. This result provides some evidence to indicate that of the two control codends, the diamond-control was the less selective for school prawns. Therefore, to maximize accuracy among comparisons of treatments for this species, only the parameter vectors derived with this control were used in subsequent tests. In contrast, the square control was used to describe the selectivity of narrow-banded sole from the 150-diamond codend because the selection curve failed to converge when using the diamond control (Fig. 2B; Table 1).

Bivariate Wald's tests failed to detect significant differences in parameters L_{50} and SR for school prawns between the two diamond-mesh treatment codends (P > 0.05), but did detect a significant difference between the 20-mm square codend and each of the diamond-mesh codends (P < 0.01). This significant difference is primarily due to the considerably higher estimated L_{50} of the square-mesh codend (Fig. 2A; Table 1). The same pattern of statistical significance was observed for narrow-banded sole, except that the significant difference was primarily due to the considerably lower estimated L_{50} of the square-mesh codend (Fig. 2B; Table 1).

Mixed-effects models with the relative efficiency parameter and L_{50} as random effects were fitted to the school prawn data (Table 2A). Catch weight was also used as a covariate to test whether it explained variability in L_{50}. It was also attempted to model SR as random, but these fits would not converge. Catch weight was significant ($P = 0.02$) for only the 100-diamond codend, and hence is not significant if the p-value is multiplied by three to correct for multiple comparisons (Table 2A). It is notable that the mixed-effects model estimated extremely large variances in L_{50}.

Analyses of catch components

ANOVA detected a significant F ratio for the main effect of codends only for numbers of total bycatch (Fig. 3C; Table 3). A priori planned comparisons (at $P = 0.05$) showed that for this variable and numbers of bycatch species, the means caught in the control codends were significantly greater than those for the treatment codends (Fig. 3C & D; Table 3). There were no significant interactions between codends and days or periods, although significant F ratios were detected for the main effects of these temporal factors (Table 3). Specifically, the weights of school prawns and bycatch were significantly different among periods, while weight of school prawns, and number of total bycatch showed an effect due to days (Table 3).

Experiment 2: lagoon seining

Thirty-four species were recorded during experiment 2, including greasyback and eastern king prawns, which comprised approx. 91 and 1.1% (by number) of the total catch, respectively. Weed (of a matted filamentous type) and jellyfish (Class Scyphozoa) were commonly present in the catch. The variability in catch weight of prawns was not as great as observed in experiment 1. Over all hauls, greasyback prawn catch varied from 1.0 kg (100-diamond codend) to 14.9 kg (control codend).

Analyses of size selectivity

Of the two control codends, only the square was used during experiment 2. This was because (i) the sizes of penaeids were known to be larger in Smiths Lake than in the Richmond River and (ii) we hypothesised that this control would have a greater water flow (owing to more open meshes) that would facilitate the release of weed and therefore reduce the likelihood of excessive masking of meshes and drag on the seine. Using this control, size-selection models were successfully fitted for greasyback prawns caught in the 100-diamond and 20-mm square codends. As with experiment 1, there was no significant reduction in deviance associated with using a Richard's curve so only the logistic models were presented (Fig. 2C; Table 4). A bivariate Wald's test detected a significant difference in selectivity of the two codends ($P < 0.01$). The estimated L_{50} and SR parameters of the 100-diamond codend were both higher than those of the square codend, but had large standard errors and were therefore estimated with high imprecision (Table 4).

The mixed-models used catch weight and the presence/absence of weed and jellyfish as potential explanatory variables to explain variability in L_{50}. None of these covariates was statistically significant for the 20-mm square codend, but presence of weed was significant for the 100-diamond codend ($P < 0.01$), effectively reducing L_{50} (Table 2B). The estimates of between-haul variability in L_{50} were noticeably smaller that those obtained from the mixed-model fits to the school prawn data from experiment 1 (Table 2). In particular, the variance of L_{50} for the square-mesh codend was just 2.4 mm, corresponding to a between-haul standard deviation of about 1.5 mm (Table 2B).

Analyses of catch components

ANOVA detected significant differences among codends for the numbers of greasyback prawns, total bycatch and bycatch species (Fig. 4B, E & F; Table 5). A priori planned comparisons showed that for greasyback prawns, the difference was due to significantly greater mean catches in the square-control codend than the combined means for the treatment codends (Fig. 4B; Table 5). Similarly, significant differences were detected between treatments and the control for the two bycatch variables listed above, however significant F ratios were also detected between the two treatment codends, with the 100-diamond retaining significantly greater numbers than the 20-mm square codend (Fig. 4E & F; Table 5). There were no significant interaction terms in any of the analyses done for variables in experiment 2, although significant differences were detected among nights for all variables analysed (Table 5).

Discussion

For the river seine, the 20-mm square codend had a larger L_{50} than the diamond-mesh codends and a similar SR. These results are consistent with those recorded during some recent studies comparing diamond- and square-mesh codends in trawl and stow nets used elsewhere in NSW (Broadhurst et al. 2004; Macbeth et al. 2005). There was, however, substantial between-haul variability in catch and selectivity, as evidenced by the extremely high estimates of σ^2 L_{50}. The between-haul variability is exacerbated by the lack of school prawns below about 8-mm CL. This means that the data are concentrated over the range of CLs corresponding to only the upper limb of the selection curve, rather than over the entire effective selection range of the curve, and this is particularly true of the diamond-mesh codends. Thus, if only a small portion of the selection curve is being fitted to data, then two quite different selection curves can give very similar fits. In an extreme case, if only large prawns are caught then there will be no information on selectivity and an estimated selection curve with infeasible parameters (e.g. a negative L_{50}) could result. The extreme between-haul variability shown by the mixed-effects model fits is a consequence of this, and hence the combined-hauls results from the river-seine experiment are more useful.

In the lagoon-seine experiment, the combined-haul selectivity estimates for the 100-diamond codend had large standard errors and hence can not be considered reliable. An inspection of the raw catch data indicated that this codend retained very small prawns and released some large prawns. The mixed-effects model parameters for the 100-diamond codend are more reasonable, notwithstanding the implausible reduction in L_{50} of 26.4 mm in the presence of weed. An inspection of the weeded hauls of this codend indicated that it had negligible selectivity. This resulted in model non-identifiability because any large negative value of the weed effect corresponds to a non-selective curve. This is reflected in the misleadingly large estimated effect and SE. The weed effect explains the extreme SR fitted in the combined-hauls analysis because in weeded hauls this codend did retain very small prawns, yet in weed-free hauls it had a mean estimated L_{50} of 9.4 m and released some reasonable-sized prawns. The selectivity estimates from the combined-hauls and mixed-effects analyses of the square-mesh codend lagoon data were similar. Moreover, the square-mesh codend did not exhibit a weed effect, and between-haul variability in relative fishing efficiency (p) and L_{50} were both relatively minor.

Given the above, the river- and lagoon-seine experiments both estimated the L_{50} of the square-mesh codend to be approx. 3 mm greater than that of the diamond-mesh codends, but with reasonably similar SRs. Both experiments also showed that the square-mesh codend experienced less between-haul variability than the diamond-mesh codends. This was particularly evident in the lagoon experiment where the 100-diamond codend was rendered effectively non-selective by the presence of weed. These variations in selectivity parameters can be attributed to a combination of factors that include the different methods of operating the seines, the specific selection characteristics of the different mesh configurations, as well as the ecological features of the estuaries being fished.

A common operational characteristic of many seines, trawls and stow nets is the constant flow of water and hence tension on the netting during fishing, which maintains narrow lateral mesh openings throughout the posterior section of the gear. Further, small organisms are quickly washed into the codend, where much of the selection probably occurs. In contrast, the lagoon seine was towed for short periods and then the body and codend remained stationary (i.e. with no water flow) for up to five minutes while the wings were repositioned. The lack of tension on the netting probably resulted in an increase in lateral diamond mesh openings throughout the seine, allowing most sizes of the greasyback prawns to easily move about and escape. This would explain the slightly larger SRs observed for all treatment codends used with the lagoon seine compared with those used with the river seine.

As noted above, the selectivity of greasyback prawns was decreased in the 100-diamond codend in the lagoon-seine experiment when weed was present in the codend (Table 5). This sort of correlation has been reported elsewhere (e.g. Polet 2000) and was probably due to a combination of the weed masking the meshes throughout the posterior of the codend and the weight of the weed reducing the lateral mesh openings along its anterior walls. These effects were absent for the square-mesh design as the meshes remained open, allowing the small prawns to come in contact with open meshes along the length of the codend during towing.

While the presence of jellyfish did not seem to reduce the selectivity of the treatment codends used during the lagoon-seine experiment, there was an impact on the efficiency of the fishing operation owing to the extra time required to sort the catch. Further, large quantities of jellyfish appeared to negatively affect the condition of the prawns and bycatch (W.G. Macbeth, personal observation), presumably because of the stinging nematocysts. This not only reduces the quality of the marketable prawns, but would probably increase the mortality of small conspecifics and other bycatch that pass through the meshes or are discarded onboard the vessel. Ideally, the bycatch of large organisms like jellyfish should, if required, be addressed before or at least in conjunction with further efforts to improve the size selectivity of penaeid seines. Specifically, the utility of various types of BRD designed to exclude all organisms larger than commercially retained sizes of prawns may warrant investigation (for a review, see Broadhurst 2000).

The quantity and composition of bycatch (excluding jellyfish and weed) varied considerably between the two methods and this is reflected in the performance of the different codends tested. Overall, relatively small quantities of bycatch were recorded during the river-seine experiment: an observation consistent with previous observer-type studies done in this fishery (Gray et al. 2003). With the exception of narrow-banded sole (which could actively squeeze through the 30-mm diamond mesh, but not the 20-mm square mesh), most of the bycatch recorded during experiment 1 consisted of organisms too large to escape through the meshes of any of the codends trialled. In contrast, much of the bycatch encountered during the lagoon-seine experiment consisted of relatively small finfish, many of which were physically able to pass through the open meshes in the 20-mm square codend.

Our results have demonstrated that despite physical similarities among the two designs of penaied seines and their codends examined, inherent variability in fishing operations and local ecologies means that these gears have considerably different selectivities. It seems inappropriate, therefore, to impose the same gear-based regulations across these fisheries. For example, the utility of larger square mesh may warrant immediate examination for the Richmond River prawn-seine fishery but for the Smiths Lake fishery it is clear that other gear modifications (i.e. mechanical-type BRDs) should also be considered. In future, strategies to improve size-and species-selectivity for NSW penaeid seines, and indeed any other fisheries (penaeid or otherwise) that use these sorts of gears, would best be investigated on a fishery-specific basis.

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Table 1. Combined-hauls fits to the Richmond River data. Carapace lengths at 50% probability of retention and selection ranges (L_{50} and SR, respectively, in mm) and relative fishing efficiencies (p) for school prawns and narrow-banded sole caught in the five codends used during experiment 1. Parameters were calculated using both the diamond- and square-control codends. Standard errors are given in parentheses and have been corrected for between-haul variation. --, unable to converge model. na, not applicable.

	School prawns				Narrow-banded sole			
Codends	Diamond-control		Square-control		Diamond-control		Square-control	
100-diamond								
L_{50}	7.76	(0.37)	7.61	(0.51)	68.65	(2.94)	--	
SR	2.69	(0.73)	3.59	(1.12)	5.34	(2.61)		
p	0.52	(0.06)	0.49	(0.06)	0.57	(0.08)		
150-diamond								
L_{50}	7.48	(0.38)	7.22	(0.54)	--		62.37	(3.28)
SR	2.72	(0.72)	3.42	(1.08)			2.31	(3.07)
p	0.55	(0.05)	0.52	(0.06)			0.41	(0.05)
20-mm square								
L_{50}	10.78	(0.28)	11.61	(0.40)	52.91	(2.43)	--	
SR	3.71	(0.47)	5.03	(0.66)	4.54	(2.29)		
p	0.54	(0.10)	0.54	(0.15)	0.52	(0.06)		
Diamond-control								
L_{50}	na		--		na		32.34	(3.10)
SR							3.54	(4.21)
p							0.52	(0.03)
Square-control								
L_{50}	4.44	(1.70)	na		--		na	
SR	2.52	(2.51)						
p	0.53	(0.05)						

Table 2. Mixed-effects model fits to A) school prawn data from the Richmond River experiment and B) greasyback prawn data from the Smiths Lake experiment. Parameters estimated: means for carapace length at 50% probability of retention and selection range (μ_{L50} and μ_{SR}, respectively; units in mm), variance of L_{50} (σ^2_{L50}), and mean and variance of the logit of relative fishing efficiency (μ_q and σ^2_q, respectively where q=logit(p)), and C_{weed} (change in L_{50} with the presence of weed). Standard errors are given in parentheses. na, not applicable.† The 100-diamond data showed negligible selectivity in the presence of weed. This results in model non-identifiability because any large negative value of the weed effect corresponds to a non-selective selection curve. This is reflected in the misleadingly large estimated effect and standard error.

	Codends		
Parameters	*100-diamond*	*150-diamond*	*20-mm square*
A) School prawns – Richmond River			
μ_{L50}	5.3 (1.8)	3.3 (2.5)	10.7 (0.9)
μ_{SR}	4.7 (0.5)	4.2 (0.7)	4.6 (0.3)
μ_q	0.4 (0.2)	0.3 (0.3)	0.4 (0.3)
σ^2_{L50}	45.7 (23.4)	34.2 (15.4)	19.6 (8.0)
σ^2_q	0.9 (0.3)	1.9 (0.5)	2.0 (0.5)
B) Greasyback prawns – Smiths Lake			
μ_{L50}	9.4 (1.0)	na	12.8 (0.5)
μ_{SR}	3.3 (0.4)		4.2 (0.4)
μ_q	-0.3 (0.2)		0.3 (0.2)
σ^2_{L50}	11.4 (5.9)		2.4 (1.1)
σ^2_q	0.6 (0.2)		0.3 (0.1)
C_{weed}	-26.4(904.5)†		

Table 3. Experiment 1: summaries of F ratios from three-factor ANOVA and *a priori* planned comparisons comparing catches from five codends (3 x treatment – Treat, and 2 x control – Ctrl) tested over five days during two periods (n = 3). "Pld" indicates that the F ratio for the interaction term was non-significant at P < 0.25, and the sums of squares and df were pooled with the residual. All data were ln(x+1) transformed. **P < 0.01; *P < 0.05.

Source of variation	df	Wt of school prawns	Bycatch wt	Bycatch no.	Bycatch spp.
Codends (C)	4	0.63	0.64	2.48*	2.35
Treat vs. Ctrl	1	0.02	2.08	8.42**	8.31**
Among Treat	2	0.78	0.24	0.68	0.55
Among Ctrl	1	0.93	<0.01	0.12	<0.01
Periods (P)	1	7.87*	6.22*	0.06	0.07
C x P	4	Pld	Pld	Pld	1.64
Days (D)	8	2.43*	Pld	2.24*	Pld
C x D	32	Pld	Pld	Pld	Pld
Residual	100				

Table 4. Combined-hauls fits to the Smiths Lake data. Carapace lengths at 50% probability of retention and selection ranges (L_{50} and SR, respectively; units in mm) and relative fishing efficiencies (p) for greasyback prawns caught in the two treatment codends. The square-control codend was used. Standard errors are given in parentheses and have been corrected for between-haul variation.

	Codend			
	100-diamond		20-mm square	
L_{50}	13.48	(5.09)	13.42	(0.73)
SR	13.07	(6.06)	5.84	(0.85)
p	0.59	(0.10)	0.61	(0.03)

Table 5. Experiment 2: summaries of F ratios from two-factor ANOVA and *a priori* planned comparisons comparing catches from three codends (2 x treatments – Treat, and 1 x control – Ctrl; 100-diamond – Diam, square – Squ) tested over nine nights (n = 2). “Pld” indicates that the F ratio for the interaction term was non-significant at P < 0.25, and the sums of squares and df were pooled with the residual. All data were ln(x+1) transformed. ** P < 0.01; *P < 0.05. Weight of bycatch was tested at P = 0.01 because a Cochran’s test of the transformed data was significant at P = 0.05.

Source of variation	df	Wt of total prawns	No. of greasyback prawns	No. of eastern king prawns	Bycatch wt	Bycatch no.	Bycatch spp.
Codends (C)	2	2.84	4.95*	0.14	0.87	26.87**	6.82**
Treat vs. Ctrl	1	2.93	7.86*	0.21	1.09	48.94**	6.17**
Diam vs. Squ	1	2.74	2.04	0.07	0.66	4.81*	7.48*
Nights (N)	8	5.36**	4.69**	3.44**	5.93**	7.51**	3.67**
C x N	16	1.46	1.42	Pld	Pld	Pld	Pld
Residual	27						

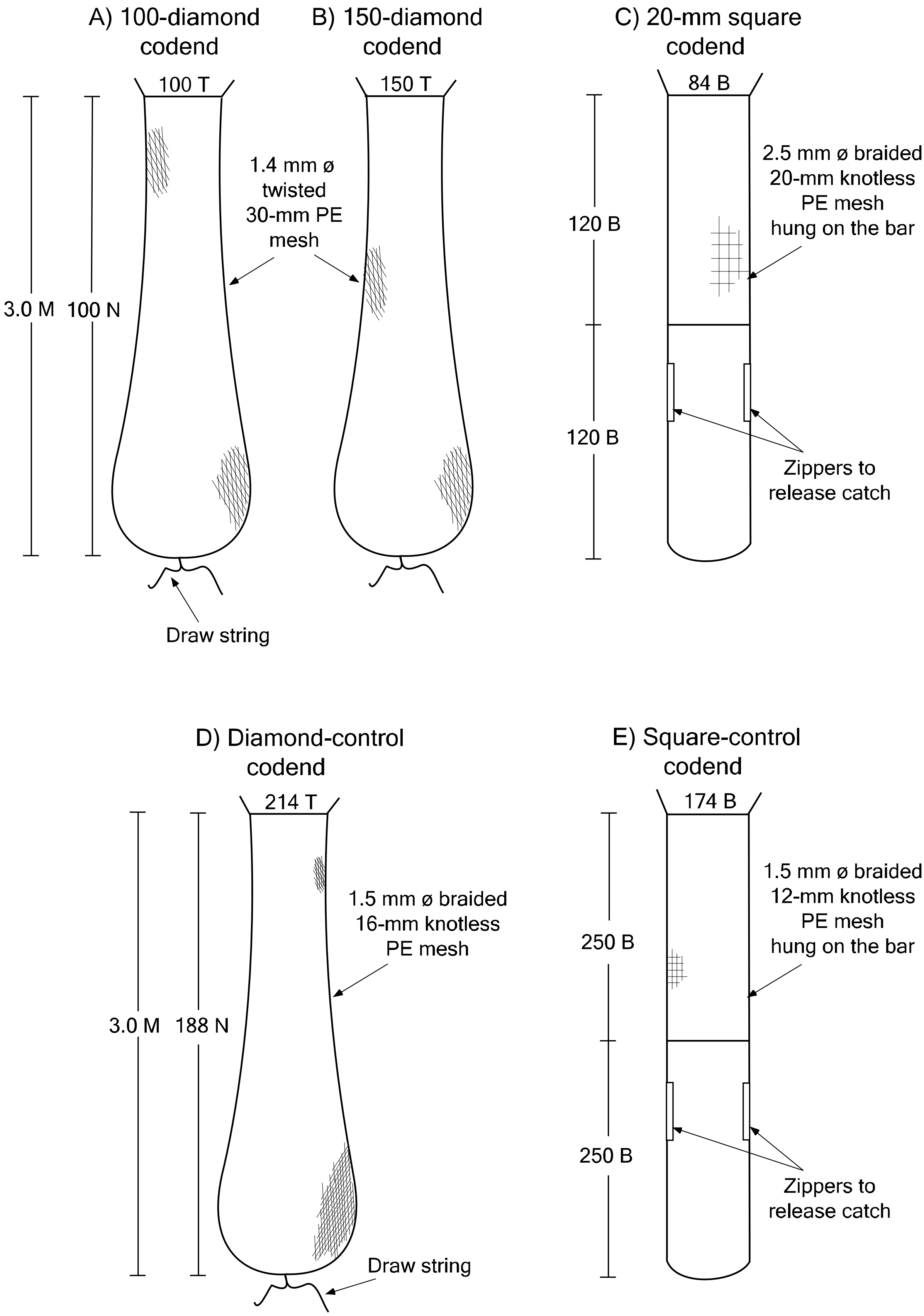
Captions to figures

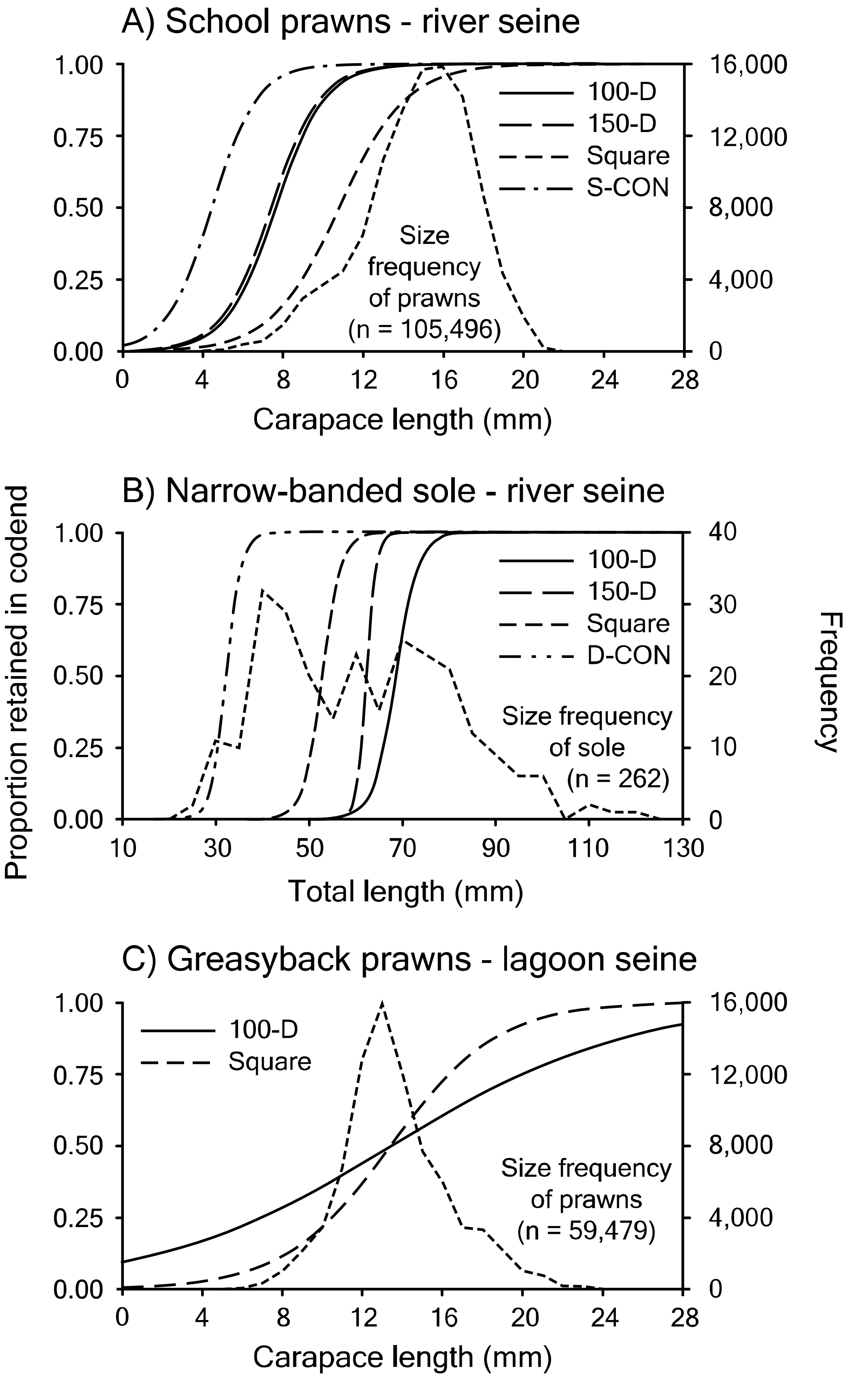
Figure 1. Schematic diagram of the A) 100- and B) 150-diamond; C) 20-mm square; and D) diamond- and E) square-control codends. N, normals; T, transversals; B, bars; M, metres.

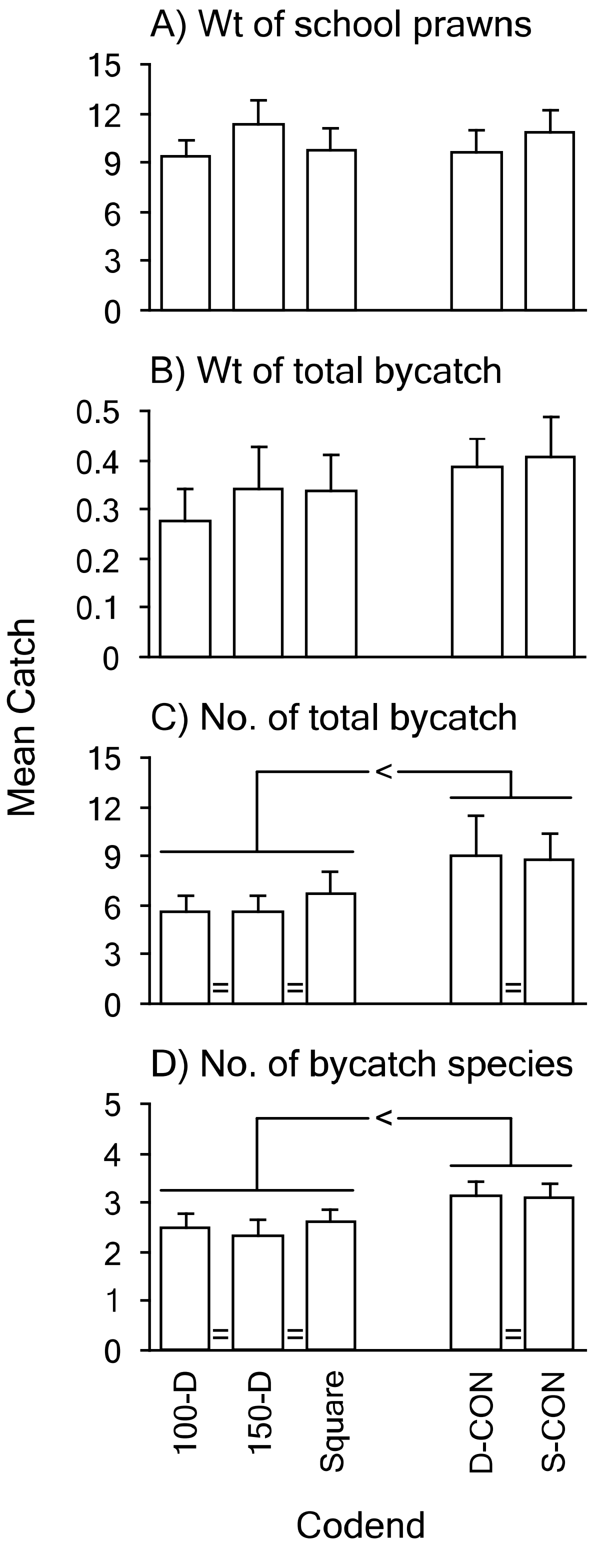
Figure 2. Logistic selection curves (where selectivity models were converged) for A) school prawns and B) narrow-banded sole caught in codends used during the river-seine experiment, and C) greasyback prawns caught in codends used during the lagoon seine experiment. 100-D, 150-D, Square, S-CON and D-CON refer to 100- and 150-diamond, 20-mm square, and diamond- and square-control codends, respectively. Size-frequency curves are for A) school prawns caught in the diamond-control codend, B) sole caught in the two control codends combined, both during experiment 1, and C) greasyback prawns caught in the square-control codend during experiment 2.

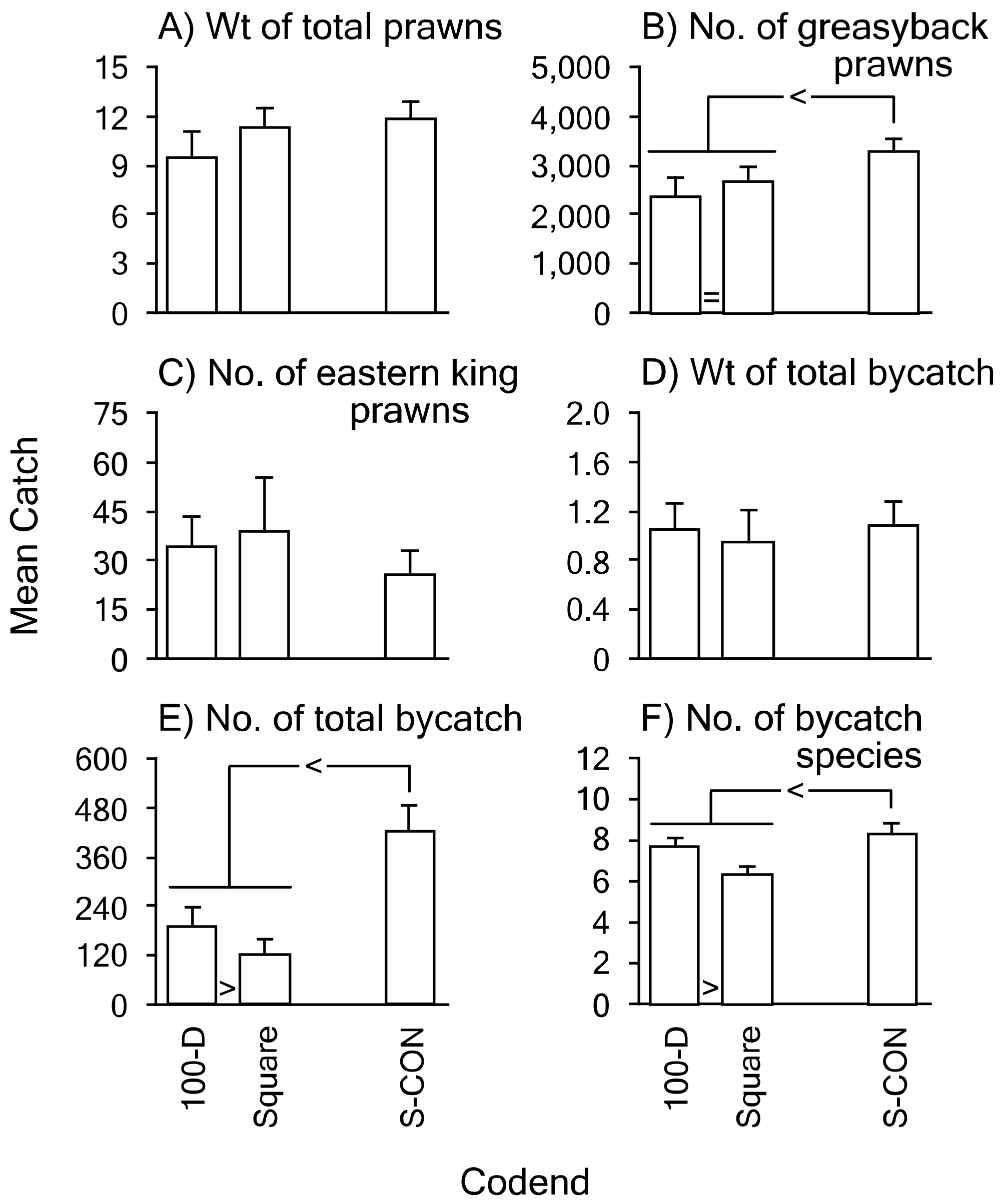
Figure 3. Differences in the mean catches (+SE) among the five codends used in experiment 1. 100-D, 150-D, Square, S-CON and D-CON refer to 100- and 150-diamond, 20-mm square, and diamond- and square-control codends, respectively. Catch data are for A) the weight of school prawns; the B) weight and C) number of total bycatch; and D) the number of bycatch species. Significant results of a priori planned comparisons are shown where applicable. Weights are in kg.

Figure 4. Differences in the mean catches (+SE) among the three codends used in experiment 2. 100-D, Square and S-CON refer to 100-diamond, 20-mm square and square-control codends, respectively. Catch data are for A) the weight of total prawns; numbers of B) greasyback and C) eastern king prawns; the D) weight and E) numbers of total bycatch; and F) numbers of bycatch species. Significant results of a priori planned comparisons are shown where applicable. Weights are in kg.


A) 100-diamond codend
B) 150-diamond codend
C) 20-mm square codend
100 T
150 T
84 B
3.0 M
100 N
1.4 mm ø twisted 30-mm PE mesh
120 B
120 B
2.5 mm ø braided 20-mm knotless PE mesh hung on the bar
Zippers to release catch
Draw string
D) Diamond-control codend
E) Square-control codend
214 T
174 B
3.0 M
188 N
1.5 mm ø braided 16-mm knotless PE mesh
250 B
250 B
1.5 mm ø braided 12-mm knotless PE mesh hung on the bar
Zippers to release catch
Draw string


A) School prawns - river seine
1.00
0.75
0.50
0.25
0.00
0
4
8
12
16
20
24
28
Carapace length (mm)
16,000
12,000
8,000
4,000
0
100-D
150-D
Square
S-CON
Size
frequency
of prawns
(n = 105,496)
B) Narrow-banded sole - river seine
10
30
50
70
90
110
130
Total length (mm)
40
30
20
10
100-D
150-D
Square
D-CON
Size frequency
of sole
(n = 262)
Proportion retained in codend
Frequency
C) Greasyback prawns - lagoon seine
100-D
Square
Size frequency
of prawns
(n = 59,479)
Carapace length (mm)


A) Wt of school prawns
15
12
9
6
3
0
B) Wt of total bycatch
0.5
0.4
0.3
0.2
0.1
0
Mean Catch
C) No. of total bycatch
15
12
9
6
3
0
<
=
=
=
D) No. of bycatch species
5
4
3
2
1
0
<
=
=
=
100-D
150-D
Square
D-CON
S-CON
Codend


A) Wt of total prawns
15
12
9
6
3
0
B) No. of greasyback prawns
5,000
4,000
3,000
2,000
1,000
0
<
=
C) No. of eastern king prawns
75
60
45
30
15
0
D) Wt of total bycatch
2.0
1.6
1.2
0.8
0.4
0
Mean Catch
E) No. of total bycatch
600
480
360
240
120
0
<
>
F) No. of bycatch species
12
10
8
6
4
2
0
<
>
100-D
Square
S-CON
100-D
Square
S-CON
Codend

Appendix 10 - Macbeth, W.G., Broadhurst, M.K., Millar, R.B. and Smith, D.A. 2004. Increasing mesh openings in codends: an appropriate strategy for improving the selectivity of penaeid fishing gears in an Australian estuary? Sub. to Mar. Freshwater Res**.**

Increasing mesh openings in codends: an appropriate strategy for improving the selectivity of penaeid fishing gears in an Australian estuary?

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Abstract
This study investigates the effects of increasing the lateral mesh openings in codends on the size- and species-selectivity of lagoon and river seines, and a stow net used to target penaeid prawns (eastern king, *Penaeus plebejus*; school, *Metapenaeus macleayi*; and greasyback prawns, *M. bennettae*) in Wallis Lake, New South Wales, Australia. Compared to conventional codends made from 36-mm diamond-shaped mesh, new designs made from 25- and 29-mm mesh hung on the bar (i.e. square-shaped mesh) significantly reduced the catches of non-target fish (by between 58 and 95%) and improved size selection for the targeted penaeids in the stow net and lagoon seine. In contrast, owing to gear-specific operational characteristics such as a slower hauling speed, there were few detectable effects of altering mesh openings in the codend of the river seine. The results are discussed in terms of the differences in the gears used and their particular selection mechanisms. We conclude that codends made from a mesh size approaching 29 mm, hung on the bar, would provide appropriate size- and species-selection for Wallis Lake stow nets and lagoon seines. Further research is required, however, to examine the utility of operational changes to river seines and/or alterations to mesh size and configuration in the wings and body to improve selectivity.

Introduction

The capture of non-target organisms (termed 'bycatch') by commercial fishing gears is a global problem that has received substantial attention in recent years (for reviews see Andrew et al. 1992; Alverson et al. 1994). In New South Wales (NSW), Australia, most attempts at mitigating bycatch have occurred in penaeid prawn-trawl fisheries and a range of bycatch reduction devices (BRDs), designed to exclude non-target organisms similar in size, or larger than the targeted species are now commonplace (see Broadhurst 2000 for a review). More recently, research has expanded to reduce the bycatch of individuals smaller than the targeted penaeids (Broadhurst et al. 2004a, b; Macbeth et al. 2004a; b; 2005). Most of this work has occurred in estuarine fisheries in response to concerns over the use of small-meshed trawls, seines, stow and trap nets in areas known to be important nursery grounds for a diverse assemblage of small organisms, including juvenile conspecifics of the targeted penaeids (Andrew et al. 1995; Gray 2001; Gray et al. 2003).

Of 49 estuaries open to commercial fishing in NSW, Wallis Lake (a barrier estuary with associated tributaries approx. 86 km2 in area - Fig. 1), is the third largest producer of wild penaeids in NSW. Three species are targeted by three different fishing gears: stow nets and river and lagoon seines. The general design of these gears is similar (i.e. funnel-shaped net bodies attached to codends), but their specific configurations (Fig. 2; Table 1a) and operations are quite different (Macbeth et al. 2004b; 2005). Stow nets are static gears (Fig. 2a), set at night in tidal channels near the mouth of the estuary (Fig. 1) between the last and first quarter moon phases to catch eastern king (Penaeus plebejus) and school prawns (Metapenaeus macleayi) migrating to oceanic waters. In contrast, river and lagoon seines are towed gears, deployed using small dories (Fig. 3 and 4, respectively). River seines are used to target school prawns during the day in the three tributaries of Wallis Lake, while lagoon seines are used at night to target greasyback prawns (M. bennettae) in the lake (Fig. 1).

Like all penaeid fisheries in NSW, those in Wallis Lake are managed by fishery-specific spatial and temporal closures, as well as common gear restrictions, including legal mesh sizes between 30 and 36 mm (stretched mesh length). Typically, 30-mm mesh is used throughout the wings and bodies of all gears and in the codends of seines. This size of mesh frequently retains large numbers of penaeids smaller than optimal commercial sizes (i.e. < 16-mm carapace length – CL), which are mostly discarded dead. In an attempt to reduce the bycatches of small eastern king prawns, all stow-net operators recently adopted 36-mm mesh throughout their codends. However, the benefits of this voluntary increase in mesh size are unclear. Studies done with penaeid-catching gears in other NSW estuaries have demonstrated that, owing to the inherently narrow lateral openings of diamond mesh in codends, a range of mesh sizes (30 to 40 mm) retained similarly unacceptable quantities of small penaeids and bycatch (Broadhurst et al. 2004a; Macbeth et al. 2004b; 2005).

One method for ensuring that lateral mesh openings are maximised in the codends of penaeid-catching gears is to orientate the meshes on the bar so that they are square shaped. Broadhurst et al. (2004a) and Macbeth et al. (2004a, b; 2005) demonstrated the effectiveness of codends made from square-shaped mesh up to 50% smaller (stretched mesh length) than conventional diamond-shaped mesh in seines, trawls and stow nets used in some NSW estuaries. In these studies, the numbers of small, unwanted penaeids and fish retained were significantly reduced (by up to 40 and 90%, respectively), while maintaining commercial catches of penaeids. However, this work also revealed considerable variability in the performance of similar, or even the same, mesh configurations among gears (see also Fonteyne and M'Rabet 1992; Broadhurst 2004b).

Variability among similarly-configured gears can be attributed to fishery-specific biological and operational factors, which have largely been ignored in current gear-based management regulations that typically aim to standardise input controls like legal mesh sizes across as many gears as possible (Macbeth et al. 2004b). While in some cases such a strategy may be appropriate, the independent quantification of the performance of mesh sizes and/or configurations across a range of conditions should, ideally, be a prerequisite to their implementation. Our aims in this study, therefore, were to: (i) quantify the size- and species-selectivities of existing stow and seine codends made from the conventionally-used diamond-shaped mesh, and (ii) determine if similarly increasing the lateral mesh openings of codends is an appropriate strategy for improving the selectivity of these three gears.

Materials and methods

Three experiments were done with chartered commercial penaeid fishers in the Wallis Lake estuary, NSW (Fig. 1), during October and November 2003. Three commercial penaeid-catching gears were used in the study: lagoon and river seines and a stow net. All gears had the same 30-mm knotted polyethylene (PE) netting (approx. 1.2-mm diameter – Ø, 3-strand twisted twine) throughout their wings and bodies, but different dimensions and configurations (Fig. 2; Table 1a). To facilitate changing codends, zippers (Buraschi S146R; 1.5 m in length – based on the maximum expected fishing circumference of the diamond-mesh codends – see Broadhurst et al. 1999) were attached to the posterior ends of the net bodies (Fig. 2).

Seven treatment codends, a control codend and a fine-meshed codend cover were constructed. All codends were made from dark netting and had a 1.5-m zipper attached transversally at their anterior end (to allow attachment to the net bodies). Three of the treatment codends represented legislated and conventional designs used with the three gears and were constructed from knotted PE mesh (1.5-mm Ø, 3-strand twisted twine) hung in the normal direction (i.e. diamond shaped). The first conventional diamond-mesh codend was made from 36-mm mesh (termed the 36D-stow codend), had a total length of 3.75 m (hanging ratio - E = 0.21) and was only used with the stow net (Table 1b). The second and third conventional designs were made from 31- and 36-mm mesh (termed the 31D- and 36D-seine codends, respectively) and had the same length (2.85 m) and hanging ratio (E = 0.33) (Table 1b). Both the 31D- and 36D-seine codends were used with the river seine but, because the selectivity of a conventional 30-mm diamond-mesh codend attached to the lagoon seine was quantified in an earlier study (Macbeth et al. 2004b), only the 36D-seine codend was used with this gear.

The remaining four treatment codends were new designs made entirely from knotless polyamide – PA mesh (2.25-mm Ø, braided twine) hung on the bar (i.e. square shaped) (Table 1b) at the same hanging ratio (E = 1). Two of the square-mesh designs were only used with the stow net and comprised 25- and 29-mm mesh hung on the bar (termed the 25S- and 29S-stow codends) with a total length of 3.75 m (i.e. the same as the 36D-stow codend) (Table 1b). The remaining two square-mesh codends (termed the 25S- and 29S-seine codends) were used with the seines and were made from the same mesh size as those above, but measured only 2.85 m in length (i.e. the same as the 31D- and 36D-seine codends) (Table 1b). The control codend was constructed for use only with the seines and comprised 16-mm knotless PA mesh (1.5 mm Ø, braided twine) hung at E = 0.31 and had a total length of 2.85 m. A 1.5-m length of 5-mm chain was sewn to the posterior margin of the codends used with the seines to create drag and prevent fouling during deployment as per the normal commercial design. Instead of using a control codend with the stow net, a cover (12-mm knotted PA, 0.9 mm Ø twisted twine) was designed to retain all organisms escaping from the treatment codends (Fig. 2a – see Macbeth et al. 2005 for full details of the cover used).

Experiment 1: selectivity of the stow net

Experiment 1 was done over five consecutive nights during the ebb tides between the last quarter and new moon phases. On each night, the stow net with codend cover attached (Fig. 2a; see Table 1a for specifications), was positioned at a randomly–selected commercial site in the tidal channel (all sites were < 3 m in depth; current flow was 1.0 - 2.5 ms-1) (Fig. 1). The 36D-, 25S- and 29S-stow codends were alternately attached to the stow-net body (inside the cover) and deployed for 20 minutes. On each night, we attempted three replicate deployments of each treatment codend in a randomised block design (i.e. 3 blocks x 3 codends).

Experiment 2: selectivity of the river seine

The river-seine experiment was done over five days at sites (between 12 – 15 m in depth) in the Wallamba River (Fig. 1). On each day of fishing, the control, 31D-, 36D-, 25S- and 29S-seine codends were alternately zippered to the body of the river seine (Fig. 2b) and the entire gear deployed using two dories. The fishing method involved securing one end of the hauling rope to an anchored winch dory (Fig. 3a) and deploying the entire seine from a haul dory in an arc around the area to be fished (Fig. 3b). The haul dory then transferred the second hauling rope to the winch dory and the seine was retrieved at approx. 0.2 ms-1 (Fig. 3b and c). This entire process took 20 minutes. On each day, we attempted two replicate deployments of each codend in a randomised block design (i.e. 2 blocks x 5 codends).

Experiment 3: selectivity of the lagoon seine

The lagoon-seine experiment was done over five nights in Wallis Lake in depths of approximately 4 m (Fig. 1). The control, 36D-, 25S- and 29S-seine codends were alternately zippered to the body of the lagoon seine (Fig. 2b), and the hauling rope-seine configuration deployed from a dory in semi-circular configuration around the area to be fished (Fig. 4a). The hauling ropes were then secured to the dory and the entire seine configuration towed for 10 minutes at a speed of approx. 0.5 ms-1 until the wings of the seine came together (Fig. 4b). At the end of this towing period, the wings and body of the seine remained stationary in the water (for up to three min) while the codend was retrieved (using a buoy and ropeline), lifted onboard and emptied. The hauling ropes and wings of the seine were then repositioned for the next deployment (i.e. Fig. 4a). On each night of fishing we attempted three replicate deployments of each codend in a randomised block design (i.e. 3 blocks x 4 codends).

Data collected

Each replicate codend (or cover) catch was separated into different species. The following categories of data (where applicable) were recorded: the weights and numbers of each species of penaeid and their CLs to the nearest 1 mm (either all penaeids or a subsample of approx. 250 were measured for each species); the total weight of bycatch and the number of individuals in the bycatch; and the numbers of all species (or groups; see below) of teleosts, cephalopods and other crustaceans comprising bycatch. Owing to difficulties with species identification, Ambassids, Gobiids, Monocanthids, Paralichthyids and Tetraodontids were grouped as ‘glassy perchlets’, ‘mixed gobies’, ‘leatherjackets’, ‘flounders’ and ‘toadfishes’, respectively.

Analyses of species selectivity

Non-metric multivariate analyses were used to investigate the effect of mesh type on the composition of the catches by each of the three gears. For each experiment, counts for all species were fourth-root transformed to reduce the influence of the more abundant species (or groups) and similarity matrices were constructed using the Bray-Curtis similarity measure. Patterns of catch composition were visually explored using non-metric multidimensional scaling (MDS) and tested for differences among mesh types using analysis-of-similarities (ANOSIM). Where ANOSIM detected significant differences, the species or groups primarily responsible for these dissimilarities were determined using similarity-percentages (SIMPER) analysis. To assess the influence of mesh type on the variability in composition of catch amongst replicates for each of the gears, the index of multivariate dispersion (IMD) was determined for each mesh type using the MVDISP program. All multivariate analyses were done using PRIMER (Clarke and Gorley 2001).

General catch variables (weights of total penaeids and the numbers of total bycatch individuals and bycatch species) were compared using appropriate parametric two-factor analyses of variance (ANOVA) with codends and nights/days considered fixed and random factors, respectively. Data were ln(x+1) transformed (to model treatment effects as approx. multiplicative) and tested for heterocedasticity using Cochran’s test. Data sets showing significant heterocedasticity were analysed at a significance level of $P = 0.01$ in the ANOVA to counteract the increased probability of type I error. In all analyses, where the interaction term was non-significant at $P = 0.25$, it was pooled with the residual to increase the power of the test for the main effect of codends. Significant

F-ratios for the main effect of codends were investigated using Student-Newman-Keuls (SNK) multiple comparisons, while any significant differences among days or nights were noted, but not considered further.

Analyses of penaeid size selectivity

For each gear type, the size-frequencies foreach species of penaeid caught in each replicate deployment of each codend were scaled (to adjust for subsampling), and then vertically stacked. Millar et al. (2004) showed that analysis of these stacked frequency data is equivalent to analysis of the frequencies that would be obtained by summing over all deployments, but also permits between-haul variation to be quantified. Logistic and Richard's models were fitted to these data using maximum likelihood and REP corrected for over dispersion arising from between-haul variation (Millar *et al.* 2004). The fits for the river and lagoon seine used the estimated-split (p) SELECT model for trouser trawls (Millar and Walsh 1992; Millar *et al.* 2004). All fits were implemented using ccfit and Rep.ttfit (free R functions available from www.stat.auckland.ac.nz/~millar/selectware/code.html). Successfully-converged models were assessed by comparing deviances and associated degrees of freedom against a chi-squared distribution and by visual examination of residual plots. Where appropriate, the bivariate form of Wald's F-test was used to detect significant differences between selection curves (Kotz *et al.* 1982).

Results

Experiment 1: selectivity of the stow net

Due to unfavourable working conditions, only one block of replicate codend (and cover) deployments was possible on the fourth night. All of the size-frequency data collected during this night were used in selectivity analyses, but to maintain a balanced ANOVA design, the catch data for the fourth night were excluded, reducing the total number of replicate samples (n) to 12.

Eastern king and school prawns comprised approx. 52 and 22% (by number) of the total catch (approx. 29,900 individuals), respectively. A total of 40 bycatch species (or groups) was recorded, although 87% of this bycatch comprised four teleosts: Australian anchovy (Engraulis australis), whitebait (Hyperlophus vittatus), fortescue (Centropogon australis) and tailor (Pomatomus saltatrix).

Species selectivity

MDS showed clear differences in catch structures among and within codends (Fig. 5a). The greatest variation occurred among replicates in the 29S-stow codend (IMD = 1.243), followed by the 25S- and 36D-stow codends (IMD = 1.004 and 0.753, respectively). Overall there was a significance difference in catch composition among codends ($R = 0.19$, $P < 0.01$). Pairwise comparisons further indicated that there were no differences between the two square-mesh codends ($R = 0.001$, $P > 0.05$), but that both were significantly different to the 36D-stow codend ($P < 0.01$). As a consequence, SIMPER analysis was used to compare catch composition between the square-mesh codends (25S- and 29S-stow pooled) and the 36D-stow codend. Differences were found to be primarily associated with greater abundances of penaeids and bycatch species in the square-mesh and 36D-stow codends, respectively (Table 2a).

ANOVA did not detect significant differences among treatment codends for the weight of total penaeids (Fig. 6a; Table 3a), although significant F ratios were detected for the numbers of bycatch individuals and bycatch species (Fig. 6b and c; Table 3a). There was also a significant difference among nights detected for the number of bycatch individuals (Table 3a). Similar analyses using the totals retained in the codend and cover combined (for each replicate) did not detect any significant differences among codends for any of the variables ($P > 0.05$; Fig. 6a – c). SNK tests showed that the two square-mesh codends retained significantly fewer bycatch individuals and bycatch species than the 36D-stow codend (means reduced by up to 88% - Fig. 6b and c); attributed to the substantial reductions in the numbers of Australian anchovies and whitebait by the square-mesh codends (Table 2a).

Size selection of penaeids

Parametric size-selection curves were successfully converged for school (all logistic models) and eastern king prawns (all Richard's models) for all treatment codends (Fig. 7b and d; Table 4a). Significant differences in parameter vectors were detected among all codends for each species (Wald's tests, $P < 0.01$; Table 4a), except between the 36D- and 25S-stow codends for school prawns (Wald's test, $P > 0.05$; Table 4a). For both species, the L_{50}s for the 29S-stow codend (18.43 and 18.07 mm CL, respectively) were greater than the 36D-stow (15.12 and 15.20 mm CL, respectively) and the 25S-stow codends (15.14 and 14.41 mm CL, respectively) (Fig. 7b and d; Table 4a). Conversely, the SRs for school and eastern king prawns caught in the 36D-stow codend (5.41 and 8.27 mm, respectively) were greater (though not significantly for 36D- vs. 25S-stow codend) than those for both square-mesh codends (which ranged between 3.31 and 4.29 mm) (Fig. 7b and d; Table 4a).

Experiment 2: selectivity of the river seine

Most of the total catch (approx. 205,800 individuals) comprised school prawns (approx. 99% by number). Of the 18 bycatch species (or groups) recorded, four teleosts comprised 88% of the total catch (in order of decreasing abundance); glassy perchlets, mixed gobies, silver biddy (Gerres subfaciatus) and southern herring (Herklotsichthys castelnaui).

Species selectivity

MDS revealed little variability among codends, but some variation within replicate deployments of individual codends (Fig. 5b). The lack of definitive grouping was supported by ANOSIM which returned non-significant results for the global ($R = -0.032$, $P > 0.05$), and all pairwise comparisons ($R < 0.08$, $P > 0.05$ for all contrasts). The greatest variability among replicate hauls occurred in the 29S-seine codend (IMD = 1.332) followed by the 25S-seine codend (IMD = 1.069). The two outlying data points in Fig. 5b, which inflated the variability associated with the square-mesh codends, resulted from unusually low catches of school prawns for those hauls. Their removal from the analyses did not reveal any grouping. The least variability was demonstrated by the 35D-seine codend (IMD = 0.707), with the control and 31D-seine codends (IMD = 0.919 and 0.972, respectively) intermediate between this and the square-mesh codends. Due to the lack of significant differences between codends, SIMPER analyses were not done. Similarly, ANOVA failed to detect significant differences among the main effect of codends (including the control codend) for any of the variables examined (Fig. 6d – f; Table 3b).

Size selection of penaeids

Models were converged for all treatment codends, although for the 25S-, 31D- and 36D-seine codends these were not significantly different than the null model (i.e. a non-selective codend) ($P > 0.05$). A valid logistic curve was generated for the 29S-seine codend with an estimated L_{50} and SR of 7.27 and 3.70, respectively (Fig. 7a; Table 4b).

Experiment 3: selectivity of the lagoon seine

The total catch (approx. 44,500 individuals) comprised greasyback (approx. 74% individuals), eastern king (7%) and school prawns (1.4%). Bycatch included 36 species (or groups), of which six comprised more than 84% of the total (in order of decreasing abundance): little siphonfish (Siphamia cephalotes), mixed gobies, silver biddy, whitebait, common stinkfish (Foetorepus calauropomus) and pink-breasted siphonfish (S. roseigaster). Large volumes of jellyfish (Class Scyphozoa) (i.e. greater than five times the volume of the catch) were present in all catches during the fifth night.

Species selectivity

MDS demonstrated two distinct, aggregated groups for the catch compositions from the control and 36D-seine codends, respectively (Fig. 5c). The two square-mesh codends formed a third group with some overlap and a greater variability in catch compositions (Fig. 5c). These patterns were confirmed by ANOSIM, which detected highly significant differences among codends ($R = 0.494$, P < 0.01), and between each pairing of codends (P < 0.01), with the exception of the two square-mesh types which were not significantly different (R = 0.064, P > 0.05). IMD analyses also indicated that, as for the stow-net and river-seine experiments, the composition of the catches in the square-mesh codends (29S- and 2SD-seine = 1.427 and 1.329, respectively) were more variable that those in the diamond-mesh (36D-seine = 0.686) and control (0.558) codends. SIMPER analyses compared catch compositions between the square-mesh (pooled) and the 36D-seine (Table 2b) and control (Table 2c) codends. For each comparison, the square-mesh codend catches had lower abundances of all the major contributing species or groups. Although this included the targeted greasyback prawns, the mean abundances for this species were only slightly lower.

ANOVA did not detect a significant difference among codends for the weight of total penaeids (Fig. 6g; Table 3c), although significant differences were detected for the numbers of bycatch individuals and species (Fig. 6h and i; Table 3c). Subsequent SNK tests showed that of the treatment codends, the two square-mesh designs retained significantly fewer individuals of bycatch than the 36D-seine codend (P < 0.01; Fig. 6h), mainly due to reductions in the numbers of little siphonfish, mixed gobies and whitebait retained in the square-mesh codends (Table 2c). No definitive order was detected among codends for the number of bycatch species (P > 0.05; Fig. 6i). All variables showed a significant effect due to night, but no interactions with codends (Table 3c).

Size selection of penaeids
Logistic selection curves were successfully converged for greasyback prawns for all of the treatment codends (Fig. 7f; Table 4c). However, models could only be fitted for school prawns caught in the 25S-seine codend and eastern king prawns caught in the 36D- and 25S-seine codends (Fig. 7c and e, respectively; Table 4c). The three selection curves for greasyback prawns were significantly different from each other (Wald's tests, P < 0.01; Fig. 7f; Table 4c), with the 36D-seine codend having the largest (although not reliably estimated due to large standard errors) L_{50} and SR (19.43 and 15.09 mm, respectively; Table 4c). The 25S- and 29S-seine codends had smaller L_{50}s (12.68 and 17.70 mm, respectively) and much smaller SRs (2.24 and 6.70 mm, respectively), with substantially lower associated variability (Fig. 7f; Table 4c). In contrast, the estimates of L_{50} and SR for eastern king prawns caught in the 36D-seine codend (9.28 and 2.41 mm, respectively) were smaller than those for the 25S-seine codend (13.60 and 2.73, respectively), with the curves also being significantly different (Wald's tests, P < 0.01; Fig. 7e; Table 4c). The L_{50} and SR for school prawns caught in the 25S-seine codend were 14.62 and 2.43 mm, respectively (Fig. 7c; Table 4c), although these estimates have relatively large standard errors due to lack of data.

Discussion
This study has further illustrated the utility of codends made from square-shaped mesh for significantly improving the size- and species-selectivity of penaeid-catching gears (Thorsteinsson 1992; Tokaç et al. 1998; Broadhurst et al. 1999; 2004a; Macbeth et al. 2004a, b; 2005), but has also demonstrated that gear-specific selection mechanisms potentially preclude standardizing such simple modifications among similarly-configured gears. The latter demonstrates the need for adequate identification of the key factors that influence the selectivity of particular gears as a prerequisite to the design and development of modifications that reduce unwanted bycatches (Broadhurst 2000).

As with most penaeid-catching gears (e.g. Sobrino et al. 2000; Broadhurst et al. 2004a; Macbeth et al. 2004a, b; 2005) and towed gears in general (e.g. Pope et al. 1975; Reeves et al. 1992; Wileman et al. 1996), the codend appeared to have a major influence on the overall selectivity of the lagoon seine and stow net. This is evident by the significant changes to size- and species-selection in these gears, which can be attributed to the greater lateral mesh openings in the codend (Fig. 5 – 7; Table 2 – 4). In contrast, there were no detectable effects on gear selectivity associated with changing either the size or configuration of mesh in the codend of the river seine, apart from the escape of some small school prawns from the 29S-seine codend (Fig. 7a ;Table 4b). These differences can be directly attributed to gear-specific operational characteristics and, in particular, the relatively slow hauling speed of the river seine (e.g. 0.2 ms-1) compared to the other gears (e.g. > 0.5 ms-1). We observed that during retrieval, most school prawns remained in the wings and body (which were characterised by diamond-shaped meshes with narrow lateral openings) of this seine and only passed into the codend when it was lifted onboard. This explains the apparent lack of selection in nearly all of the river-seine codends, irrespective of the mesh, and is consistent with observations made during a previous study to quantify the selectivity of similarly-hauled penaeid seines in another south-eastern Australian estuary (Broadhurst et al. 2004c).

Both the stow net and lagoon seine were fished in relatively fast water flows (up to 2.5 and 0.5 ms-1, respectively) which would have directed their entire catches into the codends, where most selection apparently occurred. Given the similar configurations of the three gears (Fig 2; Table 1), selection in the river seine probably could be augmented by increasing the hauling speed to at least 0.5 ms-1, so that, like the lagoon seine and stow net (and comparable gears in other fisheries - Macbeth et al. 2004b), the catch is washed into the codend. Alternatively, because the existing operation and slow hauling speed of the river seine appear to facilitate contact between penaeids and the meshes in the wings and body of the gear, it might be possible to modify these areas of the gear so that they maintain sufficient openings and promote selection.

The influences of operational characteristics, such as water flow, may also explain some of the differences observed in the performances of the various codends between the lagoon seine and stow net. For example, the 25S-stow codend appeared to select eastern king and school prawns at slightly larger L_{50}s and wider SRs than the comparably configured 25S-seine codend (Fig. 7; Table 4). Similarly, despite having a greater mesh circumference, lower hanging ratio (Table 1) and, therefore, reduced lateral mesh openings (Broadhurst et al. 2004a), the 36D-stow codend selected eastern king prawns at a much greater L_{50} and across a wider SR than did the 36D-seine codend (Table 4). The variable, but greater flow of water through the stow net (up to four times faster than the seine) probably forced more small eastern king prawns through the open meshes in the codend, corresponding to selection over a slightly larger range of sizes. Differences in water flow due to operational procedures may have also at least partly contributed towards some of the observed differences in size selection among codends for greasyback prawns in the lagoon seine. For example, the wide SR and high variability associated with the parameter estimates of the diamond-mesh codend compared with those of the square-mesh designs for this species may have been due to lack of any water flow through the codend when the seine was stationary, immediately prior to codend retrieval. The lack of tension on the diamond meshes would have resulted in a temporary increase in lateral mesh openings throughout the diamond-mesh codend (but not the square-mesh codends), allowing greasyback prawns to escape across most sizes. It is also likely, however, that other factors such as inter-specific differences in behaviour and/or spatial distribution of the penaeids also affect selection, since eastern king prawns did not similarly escape across such a range of sizes. Further work needs to be done to identify the key mechanisms influencing these results.

The different assemblages of bycatches retained by the stow net and lagoon seine preclude a comparison of the potential effects of operational differences on the escape of other organisms, and especially fish, from the codends of these gears. Owing to their small sizes (i.e. mostly < 10 cm total length) relative to water flow (Bainbridge 1958), few of the species (e.g. anchovies, whitebait, siphonfish, trumpeter and gobies – Table 2) would have been able to maintain position in the gears (e.g. Wardle 1983; Watson 1989). Like penaeids, most of these fish would have been quickly forced against the meshes in the various codends, where selection was probably a function of their morphology in relation to the available mesh openings. A greater maintenance and uniformity of openings in the square-mesh codends compared to the diamond-mesh designs means that many small fish could escape (e.g. a mean reduction in number of total bycatch individuals by between 58 and 95% - Fig. 6a – c and g – i; Table 2). The large observed variation in catch compositions between replicate hauls of the various square-mesh codends (i.e. IMD values > 1.0 - Fig. 5) probably reflects spatial and/or temporal variations in the sizes of these individuals or species, in relation to the mesh openings.

The reductions in SRs and corresponding maintenance and/or increases in L_{50}s for nearly all penaeids by either the 25- or 29-mm square-mesh codends demonstrates the potential of these sorts of modifications to positively benefit penaeid fisheries in Wallis Lake. At present, there are no minimum legal sizes for any penaeids in NSW, although Wallis Lake stow-net and lagoon-seine fishers seek to retain catches of all species at an approximate ‘count’ (number of penaeids 500 g-1) of 120, which corresponds to mean CLs of between 17 and 19 mm with a minimum size of approx. 16 mm. Greasyback and school prawns are thought to mature at CLs greater than 16 mm (Dall 1958) and 18 mm (Glaister 1978), respectively, and exist as more or less discrete, estuary-specific stocks (Salini 1987). Given the results presented here, it is apparent that a mesh size approaching 29 mm hung on the bar in the codend would allow large proportions of maturing school and greasyback prawns to escape stow nets and lagoon seines, respectively. Unlike these species, eastern king prawns start maturing after they have migrated offshore (at between 34 and 42 mm CL - Glaister et al. 1983; Courtney et al. 1995) and so only juveniles are retained by estuarine gears, irrespective of the mesh size or configuration. Nevertheless, given the fast growth rates of all penaeids (e.g. Glaister 1978; Glaister et al. 1987) and the high probability that individuals escaping through the meshes will survive (Broadhurst et al. 2002), any reduction in the retention of juveniles of all three species could potentially benefit their stocks.

This study has demonstrated that, like nearly all other penaeid fishing gears used in NSW, the selectivities of the conventionally rigged Wallis Lake penaeid-catching gears are not appropriate for the targeted sizes of penaeids, but that significant improvements can be achieved (in most cases) via simple alteration to the size and configuration of meshes in the codend (e.g. Broadhurst et al. 2004a; Macbeth et al. 2004a, b; 2005). Similar sizes and configurations of mesh could have application in other penaeid fisheries in NSW and elsewhere (e.g. Vendeville 1990), although their utility would need to be assessed on a fishery-specific basis with regard to the key mechanisms influencing selection.

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Table 1. Specifications for (*a*) gears, and (*b*) codends, used during the experiments. m, metres; M, meshes; N, normals; T, transversals; B, bars. na, not applicable.

	Gear type		
(a) Gear specification	Stow net	River seine	Lagoon seine
Headline length (m)	20	40	140
Footrope length (m)	20	40	140
Wing depth (M)	200	100	100
Mouth circumference (M)	800	300	--
Hauling rope length (m)	na	200	100
Spreader bar	no	yes	yes
Codend length (m)	3.75	2.85	2.85
Water flow / hauling speed (ms^{-1})	1.0 – 2.5	0.2	0.5
(b) Codend	Circumference	Length	Hanging ratio
36D-stow	200 T	96 N	0.21
31D-seine	150 T	95 N	0.33
36D-seine	125 T	74 N	0.33
25S-stow	102 B	246 B	1
29S-stow	88 B	216 B	1
25S-seine	102 B	196 B	1
29S-seine	88 B	166 B	1
Control	300 T	179 N	0.31

Table 2. Summary of SIMPER analysis listing the species primarily responsible for the differences in catch compositions between the square-mesh (25S and 29S pooled) codends and the 36D codends for the (*a*) stow-net and (*b*) lagoon-seine experiments, and the square-mesh and control codends for the (*c*) lagoon-seine experiment. The mean abundance of each species or group for each codend treatment is presented together with their percentage contribution to the overall difference between catches

Bycatch species *or group*	Mean of *square mesh*	Mean of *36D or control*	% *contribution*	Cumulative *%*
(*a*) Stow net – square-mesh codends vs. 36D-stow codend				
Australian anchovy	1.04	35.08	12.57	12.57
Eastern king prawn	321.81	203.38	10.54	23.10
Whitebait	0.46	12.08	7.21	30.32
School prawn	93.23	57.62	7.03	37.35
Fortescue	9.00	16.77	6.63	43.98
Blue sprat	0.15	2.54	6.46	50.44
(*b*) Lagoon seine – square-mesh codends vs. 36D-seine codend				
Little siphonfish	0.07	36.73	14.40	14.40
Mixed gobies	0.83	18.60	7.10	21.50
Whitebait	0.50	7.07	6.75	28.25
Pink-breasted siphonfish	0.90	7.53	5.90	34.16
School prawn	4.47	7.40	5.67	39.82
Eastern king prawn	21.07	52.20	4.86	44.68
Trumpeter	2.33	2.53	4.78	49.47
Greasyback prawn	475.20	488.80	4.68	54.15
(c) Lagoon seine – square-mesh codends vs. control codend				
Little siphonfish	0.07	125.93	15.00	15.00
Mixed gobies	0.83	99.33	11.53	26.53
Whitebait	0.50	30.33	8.58	35.11
Pink-breasted siphonfish	0.90	17.87	6.33	41.44
School prawn	4.47	25.73	6.30	47.74
Eastern king prawn	21.07	104.53	5.40	53.14
Greasyback prawn	475.20	770.27	4.26	57.39

Table 3. Summaries of F ratios from two-factor ANOVA comparing the catches from codends used with the (*a*) stow net (36D-, 25S- and 29S-stow) and (*b*) river (control and 31D-, 36D-, 25S- and 29S-seine) and (*c*) lagoon seines (control and 36D-, 25S- and 29S-seine). The codends were tested over five nights/days (n = 3, 2 and 3, respectively), although only four nights of the stow-net experiment were used in the analyses. "Pld" indicates that the F ratio for the interaction term was non-significant at $P = 0.25$, and the sums of squares and df were pooled the residual. All data were ln(x+1) transformed. **$P < 0.01$; *$P < 0.05$. #, tested at $P = 0.01$ because Cochran's tests of the transformed data were significant at $P = 0.05$.

Source of variation	df	Wt of total penaeids	No. of bycatch individuals	No. of bycatch species or groups
(a) *Stow net*				
Codends (C)	2	0.39	39.61**	8.14**
Nights (N)	3	0.75	2.85	3.21*
C x N	6	Pld	Pld	Pld
Residual	24			
(b) *River seine*				
Codends (C)	4	# 2.09	2.58	0.59
Days (D)	4	3.29	2.13	2.42
C x D	16	Pld	Pld	Pld
Residual	25			
(c) *Lagoon seine*				
Codends (C)	3	2.64	52.54**	6.98**
Nights (N)	4	4.38**	5.17**	10.37**
C x N	12	Pld	1.54	2.49
Residual	40			

Table 4. Carapace lengths (in mm) at 50% probability of retention (L_{50}) and selection ranges (SR) and relative fishing efficiencies (p) for penaeids caught in the treatment codends used with the (*a*) stow net and (*b*) river and (*c*) lagoon seines. Standard errors are given in parentheses. nsel, non-selective; --, unable to converge model. * Richard's model, otherwise logistic.

Penaeid species	Selectivity parameter	Codend		
(a) *Stow net*		*36D-stow*	*25S-stow*	*29S-stow*
Eastern king prawn	L_{50}	*15.20 (0.25)	*14.41 (0.16)	*18.07 (0.18)
	SR	8.27 (1.15)	3.31 (0.20)	4.29 (0.27)
School prawn	L_{50}	15.12 (0.30)	15.14 (0.23)	18.43 (0.27)
	SR	5.41 (0.85)	3.32 (0.51)	3.24 (0.42)
(b) *River seine*		*36D-seine*	*25S-seine*	*29S-seine*
School prawn	L_{50}	nsel	nsel	7.27 (1.31)
	SR			3.70 (2.40)
	p			0.36 (0.01)
(c) *Lagoon seine*		*36D-seine*	*25S-seine*	*29S-seine*
Greasyback prawn	L_{50}	19.43 (12.72)	12.68 (0.22)	17.70 (1.70)
	SR	15.09 (9.81)	2.24 (0.37)	6.70 (1.40)
	p	0.62 (0.39)	0.47 (0.01)	0.54 (0.06)
Eastern king prawn	L_{50}	9.28 (0.50)	13.60 (0.62)	--
	SR	2.41 (0.85)	2.73 (0.51)	
	p	0.39 (0.03)	0.48 (0.04)	
School prawn	L_{50}	--	14.62 (2.48)	--
	SR		2.43 (1.00)	
	p		0.72 (0.23)	

Captions to figures

Fig. 1. The Wallis Lake estuary showing the location of the fishing grounds (circled areas) for the stow-net and river- and lagoon-seine experiments.

Fig. 2. Configuration of the (a) stow net (with cover attached) and (b) river and lagoon seines used in the experiments.

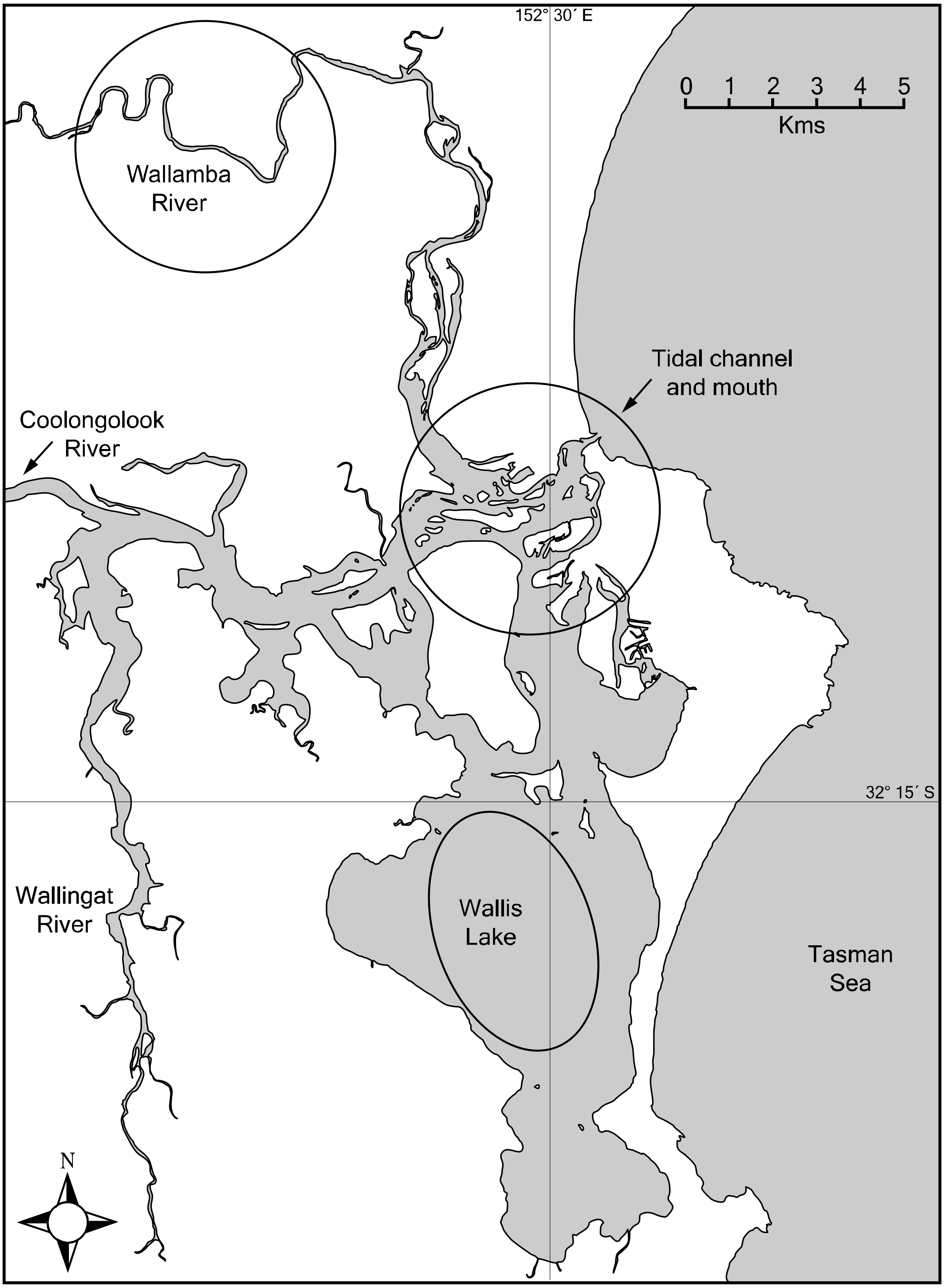
Fig. 3. Diagrammatic representation of the river-seining operation illustrating (a) deployment, and (b) and (c) retrieval of the seine.

Fig. 4. Diagrammatic representation of the lagoon-seining operation illustrating (a) deployment, and (b) towing of the seine.

Fig. 5. Non-metric MDS plots of fourth-root transformed data comparing catch compositions among codends tested during the (a) stow-net, (b) river-, and (c) lagoon-seine experiments. ■ 29- and ☐ 25-mm square-mesh; ◆ 36- and ◇ 31-mm diamond-mesh; and ● control codends.

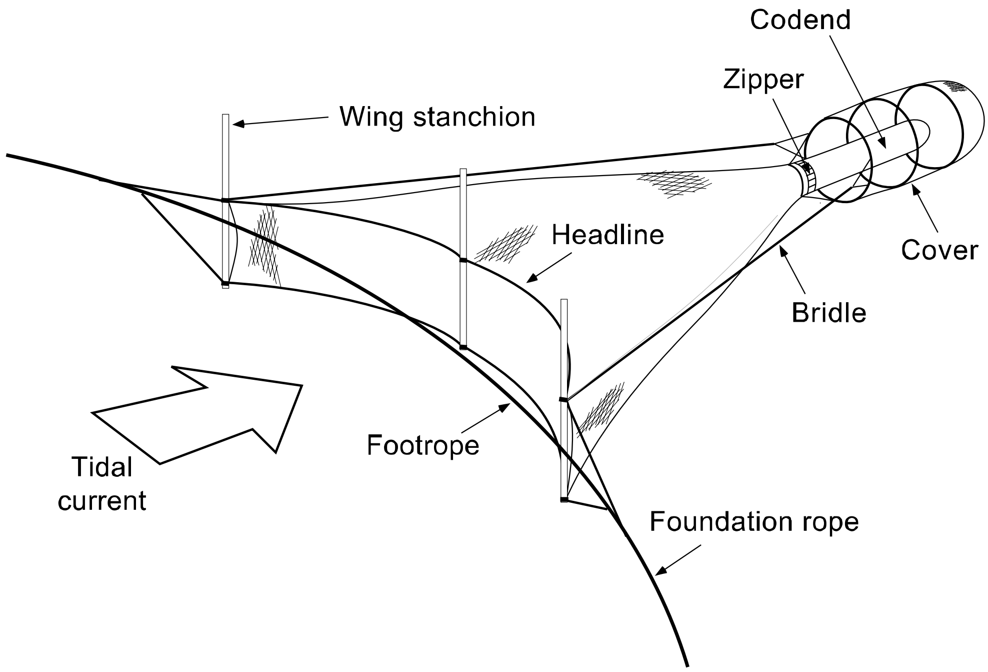
Fig. 6. Differences in the mean (+SE) weights of total penaeids and the numbers of bycatch individuals and bycatch species among the codends used during the stow-net (a – c, respectively), river- (d – f, respectively) and lagoon-seine (g – i, respectively) experiments. Data are for retained in ■ codend, and ☐ codend and cover combined (stow net, a - c); or ■ treatment, and ☐ control codends (seines, d - i). Directions (= and >) for significant differences detected in SNK tests (for catch retained in codend) are shown where applicable.

Fig. 7. Selection and size-frequency curves for school prawns caught in codends used with the (a) river seine, (b) stow net, and (c) lagoon seine, eastern king prawns caught in codends used with the (d) stow net, and (e) lagoon seine, and (f) greasyback prawns caught in codends used with the lagoon seine. Non-selective curves are not shown. (n, total number caught in codends and cover combined – stow net; or in control codend – seines).

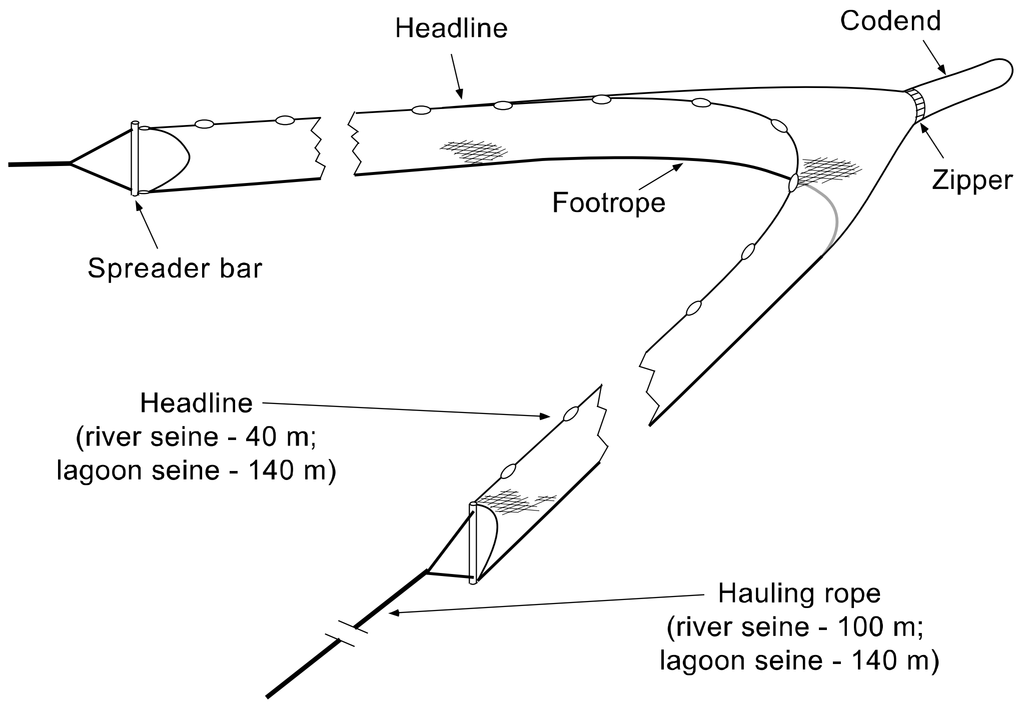


152° 30´ E
0 1 2 3 4 5
Kms
Wallamba
River
Tidal channel
and mouth
Coolongolook
River
32° 15´ S
Wallingat
River
Wallis
Lake
Tasman
Sea
N

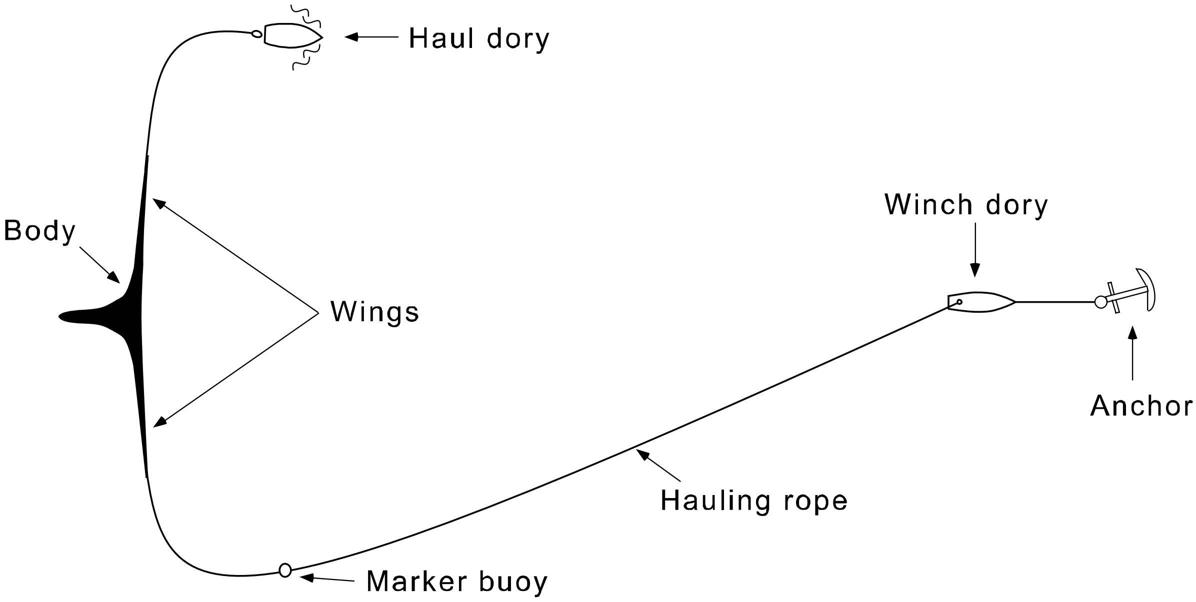
A) Stow net



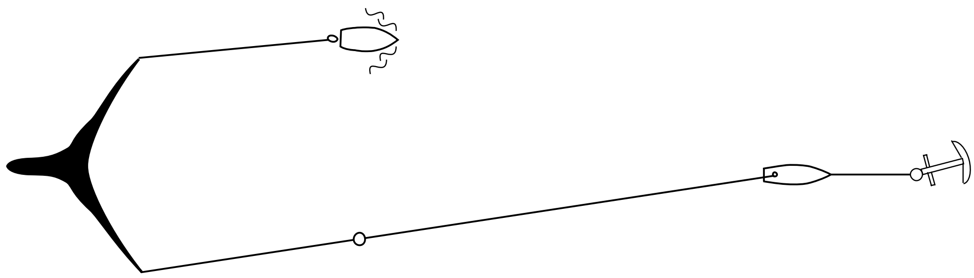
B) River and lagoon seines



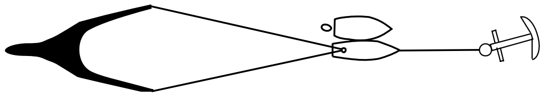
A)

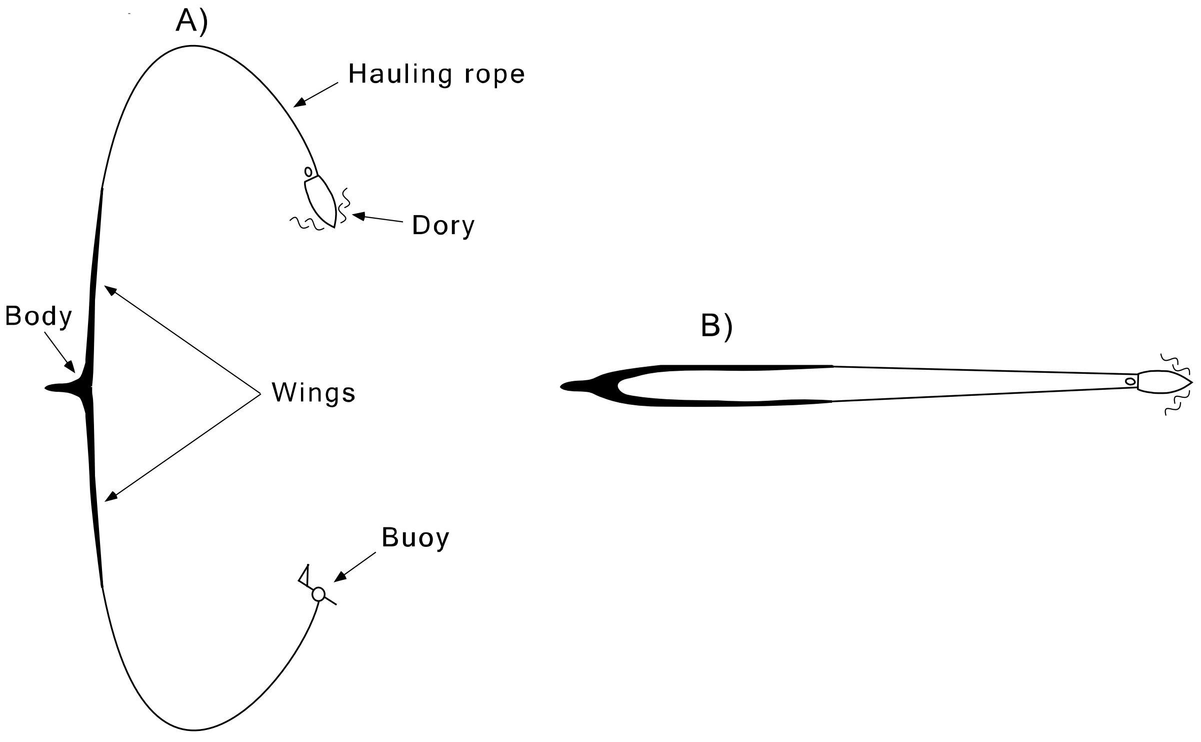

Haul dory
Body
Wings
Winch dory
Anchor
Hauling rope
Marker buoy

B)

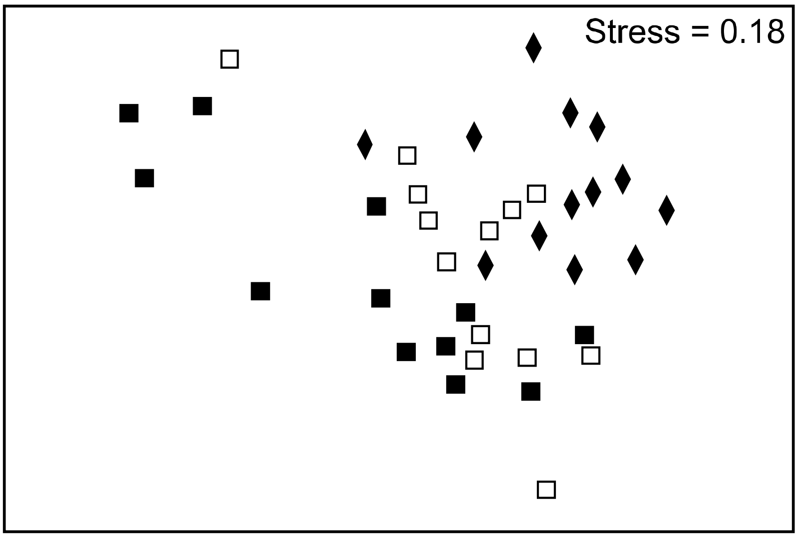


C)

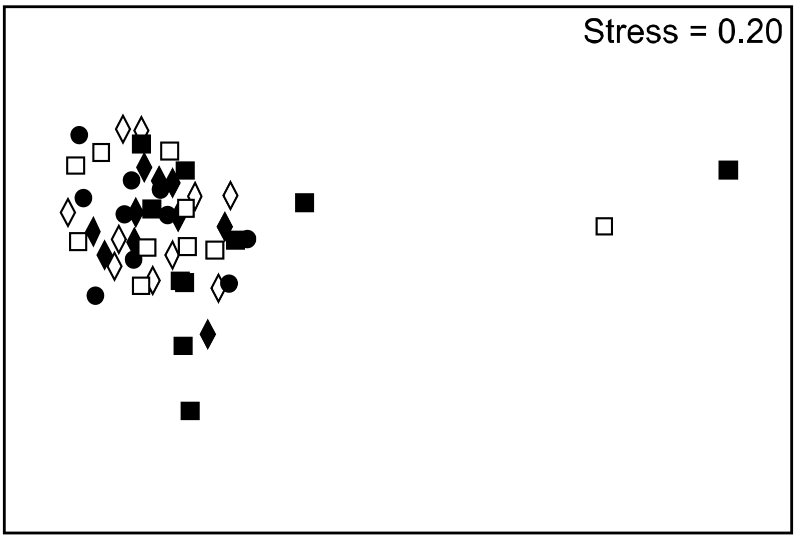



A)
Hauling rope
Dory
Body
Wings
Buoy
B)

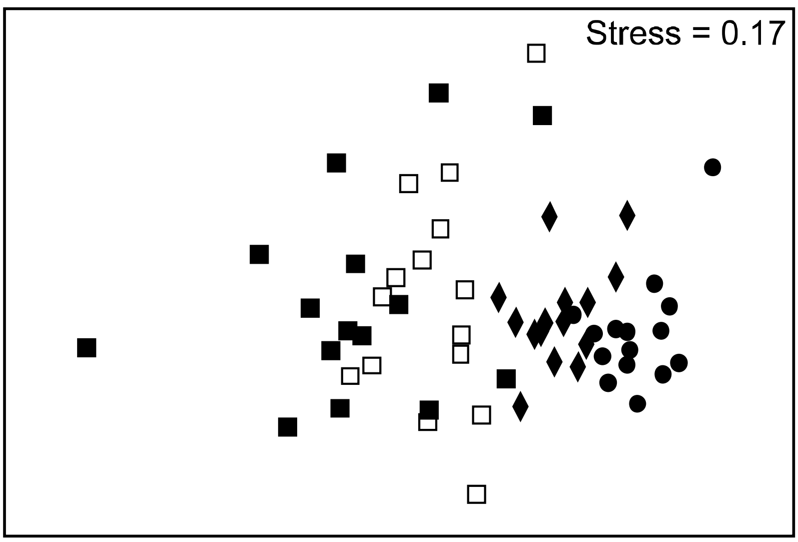
A) Stow net

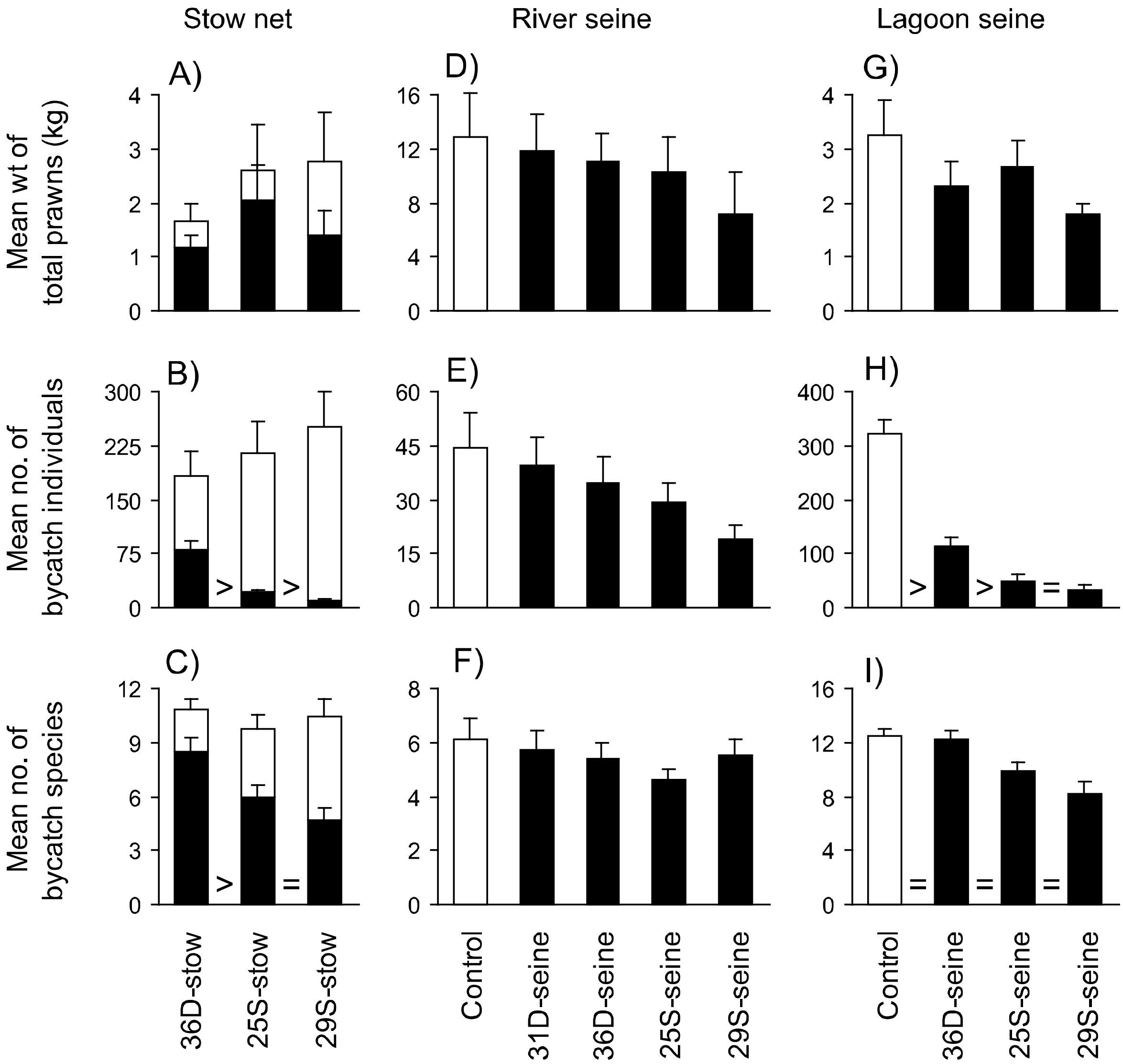


B) River seine

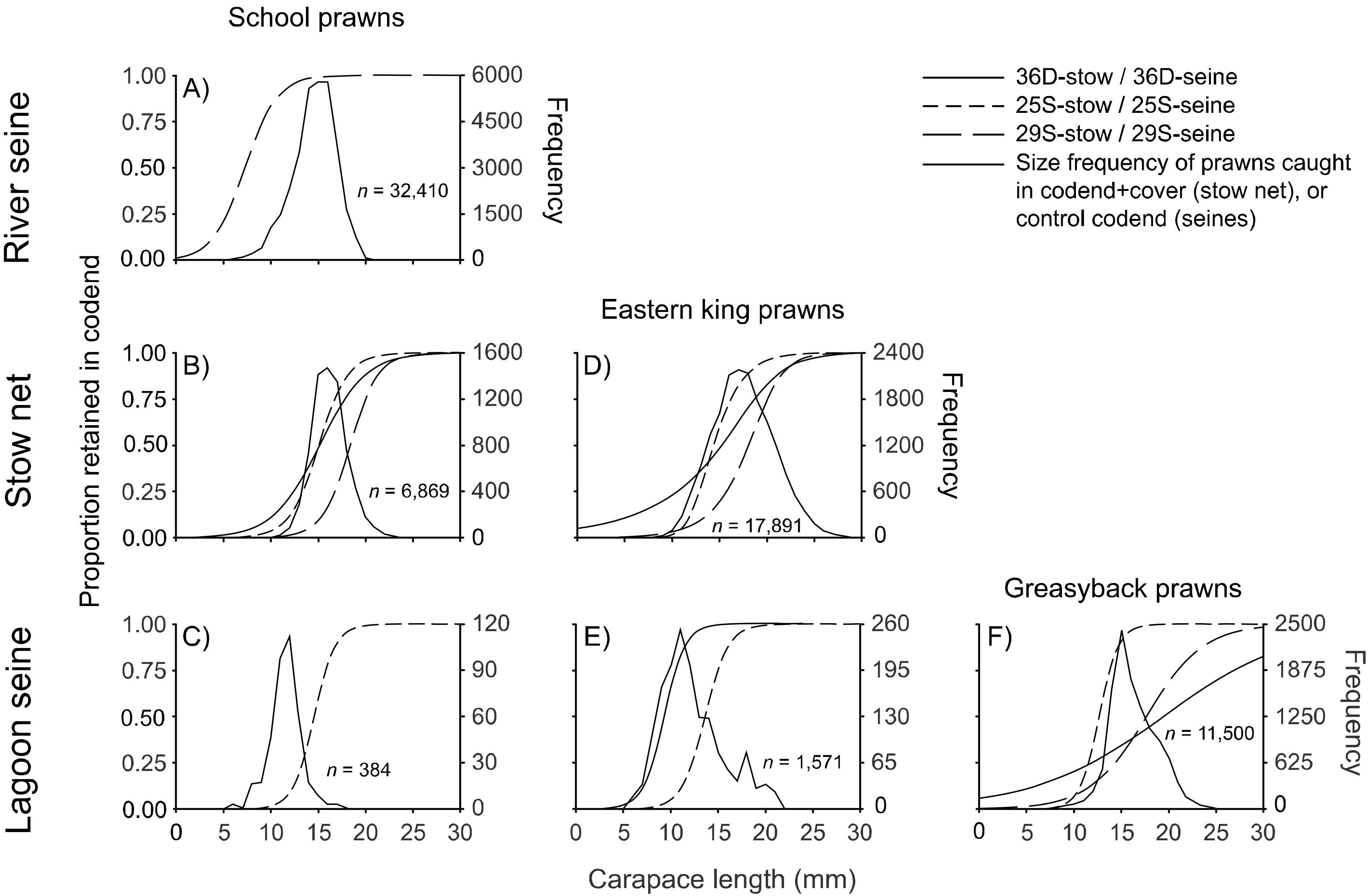


C) Lagoon seine





Stow net
River seine
Lagoon seine
A)
D)
G)
Mean wt of total prawns (kg)
B)
E)
H)
Mean no. of bycatch individuals
C)
F)
I)
Mean no. of bycatch species
36D-stow
25S-stow
29S-stow
Control
31D-seine
36D-seine
25S-seine
29S-seine
Control
36D-seine
25S-seine
29S-seine


School prawns
Eastern king prawns
Greasyback prawns
River seine
Stow net
Lagoon seine
Proportion retained in codend
Frequency
Carapace length (mm)
A)
B)
C)
D)
E)
F)
n = 32,410
n = 6,869
n = 384
n = 17,891
n = 1,571
n = 11,500
36D-stow / 36D-seine
25S-stow / 25S-seine
29S-stow / 29S-seine
Size frequency of prawns caught in codend+cover (stow net), or control codend (seines)

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Improving selectivity in an Australian penaeid stow-net fishery

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Abstract
Two experiments were done in an Australian penaeid stow-net fishery to: (i) validate the use of a fine-meshed cover for determining the selectivity of codends; and then (ii) use this cover to quantify and compare the selectivities of a conventional 30-mm diamond-mesh codend and two new square-mesh designs made from 20- and 30-mm mesh, hung on the bar. The first experiment showed that the codend cover had minimal impact on the fishing performance of the stow net. The 30-mm square-mesh codend tested during the second experiment significantly improved the selectivity of the stow net, measured as an increase in school prawn (*Metapenaeus macleayi*, Haswell, 1879) carapace length at 50% probability of retention (L_{50}), and a reduction in the unwanted bycatches of juvenile eastern king prawns (*Penaeus plebejus*, Hess, 1865) and small, non-commercial fish. However, a concomitant increase in selection range (SR) indicated that unacceptable quantities of target-sized school prawns escaped. In contrast, the 20-mm square- and 30-mm diamond-mesh codends were virtually non-selective for the sizes of school prawns encountering the gear. Compared to the 30-mm diamond-mesh codend, the 20-mm square-mesh codend did, however, reduce the quantities of eastern king prawns and non-penaeid bycatch retained. The results are attributed to the geometries of the codends tested and provide directions for future research into modifications to improve the selectivity of stow nets.

Introduction

The incidental capture of non-target organisms (termed bycatch) is a major issue facing the development of sustainable and environmentally responsible fisheries throughout the world (Saila, 1983; Andrew and Pepperell, 1992; Alverson, 1994). Of specific concern is the mortality of large numbers of juveniles of commercially important species, including conspecifics of the targeted catch. Concerns over the detrimental effects on stocks due to recruitment overfishing have led to extensive efforts to improve the size and species selectivity of fishing gears. The most common strategy for achieving this has been the development of modifications to gears that reduce unwanted bycatch.

The majority of work examining this issue has involved prawn trawls (see Broadhurst, 2000 for a review). Considerably less work has been done on other types of prawn-fishing gears like seines, trap nets and stow nets throughout the world and no work has been done with stow nets in Australia. This is despite the use of these sorts of gears throughout many temperate and tropical fisheries and the large quantities and diversities of organisms that frequently comprise their bycatches (Vendeville, 1990; Alverson, 1994; Andrew et al., 1995; Gray, 2001).

In New South Wales (NSW), Australia, stow nets are used by more than 180 operators to target penaeids in several estuaries, although the majority of effort (> 50%) occurs in the Clarence River (Andrew et al., 1995). Fishing usually occurs at night between the last and first quarter phases of the moon and involves securing a net (similar in design to a single prawn trawl) in a river or channel (often near the bank) using anchors, stanchions and/or trees (for details, see Andrew et al., 1995; Sainsbury, 1996). Prawns and other organisms move into the mouth of the anchored stow net and are washed through to the codend by the flow generated during tidal movements and/or from an anchored vessel’s propeller. All stow-net fisheries in NSW are managed by input controls that include regulations on the method of operation and gear-based restrictions such as a maximum headrope length of 20 m and a stretched inside mesh opening of 30 mm.

Stow netters in the Clarence River mainly target school prawns (*Metapenaeus macleayi*, Haswell, 1879), but at times they also catch eastern king prawns (*Penaeus plebejus*, Hess, 1865) and several species of fish (all of which are discarded; Andrew et al., 1995). In addition to legal regulations, Clarence River stow netters conform to landing a self-imposed ‘prawn count’, typically less than 120 prawns 500 g-1 (i.e. equivalent to a mean carapace length (CL) of approx. 19 mm for school prawns – Broadhurst et al., 2002). Andrew et al. (1994) observed that school prawns less than 15-mm CL are caught in the Clarence River, sorted by fishers and then discarded, often dead. The mortality of these juveniles could be reduced if they were allowed to escape from the codends of stow nets during fishing (Broadhurst et al., 2002).

One of the simplest ways to improve selectivity and reduce unwanted bycatch in trawl fisheries involves square-mesh codends (e.g. Thorsteinsson, 1992; Tokaç et al., 1998; Broadhurst et al., 1999). More specifically, for prawn trawls it is apparent that square-shaped mesh between 60 and 100% of the size of existing, conventionally-used, diamond mesh hung on the bar can facilitate significant reductions in the numbers of small prawns and fish, while still maintaining the targeted catches (Thorsteinsson, 1992; Broadhurst et al., 1999; 2004).

Several experimental methods are available for assessing the utility of these sorts of modifications to fishing gears, including alternately fishing with the treatment and control nets (e.g. Mous et al., 2002), using both gears at the same time in some sort of paired comparison (e.g. Thorsteinsson, 1992; Broadhurst et al., 1999; 2000), or attaching a cover net over the treatment fishing gear (e.g. Tokaç et al., 1998; Ragonese et al., 2002). The latter method eliminates many problems associated with inherent variability among replicate hauls over commercial fishing grounds (Broadhurst, 2000) and can provide accurate estimates of selectivity - providing the cover does not affect the normal geometry of the fishing gear and/or the behavior of organisms. The potential for such effects is of concern (Wileman et al., 1996) and so appropriate designs of covers and their assessment should be incorporated into any experimental design that employs this method. Our aims in the present study were, therefore, to: (i) validate the use of a fine-meshed cover for assessing the selectivity of stow nets, and (ii) quantify and compare the selectivities and relative efficiencies of a conventional diamond-mesh codend and two new square-mesh designs in the Clarence River.

Materials and methods

Two experiments were done using a chartered commercial prawn trawler (120 hp, 9 m in length) anchored at two stow-net sites in the Clarence River, NSW (29o 27’ S, 153o 12’ E) between the last quarter and new moon phases of June, July and August 2002. The stow net used in each experiment was a Yankee Doodle-style trawl (stretched mesh opening of 30-mm throughout) with a headrope length of 20 m and rigged to two fixed stanchions located in the river bed on either side of the stationary trawler (Fig. 1A). A zipper (Buraschi S146R, 1.5 m in length) was attached at the posterior body of the stow net to facilitate swapping of codends. During each experiment, the trawler’s motor was set at 1000 rpm to accelerate the flow of water through the stow net (Fig. 1A), as per normal fishing operations.

Three codends were constructed for this study. All codends were made from dark netting and had a total length and maximum fishing circumference of 3.0 and 1.5 m respectively. The first codend represented normal commercial designs and was termed the 30-mm diamond codend. It was made entirely of 30-mm knotted polyethylene netting (approx. 1.4-mm diameter, 3-strand twisted twine) and rigged with a conventional drawstring to close the posterior section (Fig. 2A). The second and third codends were termed the 20- and 30-mm square codends. These codends were made entirely of netting hung on the bar (i.e. square-shaped) that were 20 mm (knotless polyamide, 2.5-mm diameter braided twine) and 30 mm (the same mesh as that used in the 30-mm diamond codend) respectively (Fig. 2B and C). Circular panels of square-shaped mesh were attached to the posterior ends of these square mesh codends and, instead of a conventional drawstring, zippers (0.3 m in length) were attached to each of the lateral seams to allow removal of the catch (Fig. 2B and C). Broadhurst et al. (2004) hypothesized that these circular panels of mesh would improve the probability of organisms encountering open meshes, therefore improving their selectivity.

A hooped cover (12-mm mesh, 0.9-mm diameter twisted polyamide twine; plastic hoops) measuring between 3.6 and 4.1 m in circumference and 6 m in length was constructed so that it fitted over the entire length of a stow-net codend (Fig. 1B). The cover was designed according to the general specifications provided by Wileman et al. (1996) and was more than twice the fishing circumference and length of the various treatment codends (Fig. 1B). A zipper (1.5 m in length) was attached to the leading edge of the cover to allow attachment to the body of the stow net, immediately anterior to the codend. To eliminate the potential for any effects of drag by the cover on the stow net, two rope (8-mm, 3-strand twisted polyethylene) bridles were rigged laterally to the anterior hoop in the cover and secured to the fixed stanchions located on either side of the stationary trawler (Fig. 1A). All hydrodynamic pressure on the cover was transferred to these stanchions.

Experiment 1: assessment of the codend cover

This experiment was done to test the hypothesis that the cover had no effect on the catching efficiency of the stow net. At the start of the experiment (two days after the last quarter moon phase in July 2002), the 30-mm diamond codend was attached to the body of a stow net set in the Clarence River at depths between 2.5 and 3.5 m. On the first night of the experiment and at the start of the ebbing tide, the cover was placed over the codend, attached to the stow net and the entire assembly set in the river, behind the stationary trawler. After 45 minutes, the body of the stow net was removed from the river and the codend and cover were lifted onboard. Catches were separated and the cover was removed. The stow net (without the cover) was then set behind the vessel and allowed to fish for another 45 minutes. The two gear configurations were then used alternately so that three replicate 45-minute sets of the stow net with, and without, the cover were made on each of four nights, providing a total of 12 replicate sets for each gear configuration.

Experiment 2: assessment of the codends

This experiment was started 24 days after experiment 1 was completed (i.e. at the start of the consecutive last quarter moon phase). A stow net, with the cover attached, was located at a site in the river at depths of between 5 and 6 m. A randomized block design was used to minimize temporal effects arising due to the order in which codends were set, with a total of six 30-minute sets possible each night (two replicate sets for each codend). Therefore, within each of the two blocks completed per night, the order of the three codends was randomized. Four consecutive nights of sampling were done during each of two lunar cycles or 'moons' (i.e. immediately after the last quarter moon phases in July and August 2002). Although a total of 16 sets for each treatment codend was required for a balanced, factorial design for analyses of catches (see below), extra replicate sets were possible at times during the experiment (totals of four, two and three extra replicates for the 30-mm diamond, 20-mm and 30-mm square codends respectively), supplementing the data available for size-selectivity analyses.

Data collected and statistical analyses

After each set in each experiment, the contents of the particular codend being tested and the cover (where applicable) were emptied onto a partitioned tray. All organisms were separated by species. The following categories of data were collected for the codend and the cover net for each replicate set: the weight and number of total prawns; the weight of school prawns and a subsample (approx. 250 prawns) of their lengths (to the nearest 1-mm CL); the number of school prawns (estimated from the subsample where required); the weight, number and CLs of all eastern king prawns; the weight and number of total bycatch (comprising all other organisms); and the numbers and fork lengths (FL) of all species or groups comprising bycatch (some fish were grouped among species - see Results section).

Nonmetric multivariate analyses were used to investigate any effects of the cover on the structures and assemblages of catches in the stow net during experiment 1, according to the methodologies discussed by Clarke and Warwick (2001). Counts for all species were double square root transformed and used to develop similarity matrices based on the Bray-Curtis similarity measure. Multidimensional relationships among ranks of the similarities from individual sets of the covered and uncovered stow net codends (gear configurations) were displayed graphically in a multidimensional scaling (MDS) ordination. Two-way crossed analyses of similarity (ANOSIM) were used to test for differences in catch assemblages over the four nights of fishing. The contributions of species to the Bray-Curtis similarity were investigated using SIMPER (Clarke and Warwick, 2001).

Univariate parametric analyses were used to test the null hypotheses of no differences in catches between the various treatments examined in both experiments. One approach would be to apply generalized linear models to catch or proportion retained data, however due to the explanatory factors being a combination of fixed effects (gear configuration and codends in experiment 1 and 2 respectively) and random effects (nights in experiment 1, and both nights and moons in experiment 2), it was decided to take the more straightforward approach of fitting analyses of variance (ANOVAs) to appropriately transformed data. In experiment 1, the catch data were ln(x+1) transformed so that treatment effects would be modeled as (approximately) multiplicative. The transformed data were tested for heterocedasticity and non-normality using Cochran's and Ryan-Joiner tests respectively, and analysed using the appropriate two-factor ANOVA. Data from the codends tested in experiment 2 were expressed as the proportion that passed through the meshes of the codend and into the cover (i.e. proportion escaping from the codend) for each species (and species grouping) in each set. These data were variance stabilised using the sin-1(sqrtx) transform (Snedecor and Cochran, 1989), tested for heterocedasticity and non-normality, and then analysed using the appropriate three-factor nested ANOVA. For species that had insufficient data in experiment 2 (i.e. less than five individuals in the codend and cover combined), all temporal factors were ignored and the data were analysed for differences among codends only, using the appropriate one-factor ANOVA. In all other analyses in experiment 1 and 2, where interaction terms were non-significant at $P > 0.25$, pooling with the residual was done to increase the power of the test for the main effect of gear configuration or codends respectively. Significant F ratios detected in the ANOVAs were investigated using Student-Newman-Keuls (SNK) multiple comparisons.

The size frequencies of species caught in sufficient quantities during experiment 2 were combined across all replicate sets (including extra replicate sets) for each codend and logistic selection curves were fitted to these data using maximum likelihood. In sets where school prawns were subsampled, their size-frequencies were scaled up prior to being combined. The curves were fitted irrespective of sex, because: (i) Broadhurst et al. (2002; 2004) showed no sexual dimorphism in the length/weight relationship for school and king prawns; and (ii) fish were too small to differentiate between sexes. Likelihood ratio tests were used to detect significant differences between the selectivity models. The standard errors associated with the parameter vectors – CL or FL at 50% probability of retention (L_{50}) and selection range (SR), and differences in deviances associated with the likelihood ratio tests, were adjusted according to the replication estimate of over-dispersion – REP (Millar and Fryer, 1999; Millar et al., 2004).

Results

School prawns comprised more than 99% of the penaeid catches and 85% of total catches during both experiments (Tables 1 and 2). The bycatch included more than 32 species of teleosts, although only the commercially important southern herring and non-commercially important pink-breasted siphonfish and glassy perchlets were caught in sufficient quantities to allow meaningful univariate analyses. Owing to difficulties in their identification, gobies and gudgeons (excluding bridled goby) and glassy perchlets were grouped at the Family and Genus levels respectively (Table 1). All datasets analysed using ANOVA in each experiment were normally distributed ($P > 0.05$).

Experiment 1: assessment of the codend cover

Catch structures were not significantly different between days (averaged across gear configuration – ANOSIM Global R = 0.085) or gear configurations (averaged across all days – ANOSIM Global R = -0.009). School prawns were the dominant species, contributing to an average dissimilarity between the two gear configurations of 37.09% (Table 2). MDS had a stress of 0.1 and 0.16 for the best three- and two-dimensional ordinations respectively, indicating coherent representation of the data (Fig. 3).

ANOVA failed to detect any significant effects of the cover on the stow net for the variables examined with the exception of the numbers of pink-breasted siphonfish, which were caught in fewer numbers when the cover was attached (Tables 2 and 3). Although relatively few pink-breasted siphonfish were caught overall, a paired sign test demonstrated that greater numbers were caught in the codend with than without the cover attached for nine of the twelve replicate paired comparisons, while the inverse occurred only once ($P < 0.05$). Catches of school prawns, and the numbers of total bycatch and southern herring were significantly different among nights, but no interactions with the main effect of gear configuration were detected (Table 3).

Experiment 2: assessment of the codends

ANOVA detected significant F ratios for the main effect of codends for all variables examined (Table 4), and there was also a significant difference between moons for the number of total bycatch (Table 4A). SNK tests of the differences detected among codends showed that significantly greater proportions of the weights of total prawns and numbers of school and eastern king prawns escaped from the 30-mm square codend than either of the other designs (means between 0.32 and 0.82 compared to < 0.18 respectively) (Fig. 4A-C). Compared to the 30-mm diamond codend, significantly greater and similar proportions of the bycatch (by weight) escaped from the 20- and 30-mm square codends (mean proportions of 0.03 vs. 0.13 and 0.19 respectively) (Fig. 4D), while the numbers of bycatch and glassy perchlets escaping increased in the 20- and then in the 30-mm square codends (mean proportions of 0.18 and 0.21 vs between 0.40 and 0.95 respectively) (Fig. 4E and F).

Analyses of size selectivity

Logistic size-selection models were successfully converged for school and eastern king prawns and for glassy perchlets for all treatment codends (Fig. 5 and 6; Table 5). Only catches of school prawns in the 30-mm square codend provided sufficient data from individual hauls to allow viable estimation of over-dispersion due to between-haul variability. This estimate of REP (10.04) was used to adjust the differences in deviances from likelihood ratio tests, and the square root of REP (3.17) was used to adjust the standard errors of parameter estimates from all model fits (Table 5).

The estimated L_{50}s of school prawn and eastern king prawn for the conventionally-used 30-mm diamond codend were both below 9 mm (Table 5). There were very few prawns below 10 mm entering the codend for either species and therefore it can be concluded that the conventional 30-mm diamond codend was virtually non-selective for both penaeid species. It should be noted that the L_{50} fitted to the eastern king prawn data was 8.08 mm with standard error of 5.31. This unusually high standard error is caused by the lack of selectivity. It causes the selection curve to become near indeterminate because any very small value of L_{50} would fit the data equally well.

The 20-mm square codend had an L_{50} and SR, respectively, of 9.68 and 2.58 mm for school prawns, and 11.68 and 3.03 mm for eastern king prawns (Fig 5; Table 5). The 30-mm square codend selected school and eastern king prawns, respectively, at L_{50}s of 16.05 and 16.59 mm, with SRs of 4.76 and 3.35 mm (Fig. 5; Table 5). Likelihood ratio tests confirmed that for both species the 30-mm square codend was significantly different from the 30-mm diamond and the 20-mm square codend ($P < 0.01$). Although the fits suggest that the 20-mm square codend has better selectivity than the 30-mm diamond, these two codends were not significantly different ($P > 0.05$; Fig. 5; Table 5), possibly due to lack of statistical power arising from the small number of prawns in the size range over which these gears are selective.

Compared with the 30-mm diamond, the 20-mm square codend significantly improved the selection of glassy perchlets ($P < 0.01$), increasing the L_{50} from 33.57 to 46.40 mm, with negligible change in SR (Fig. 6; Table 5). Very few glassy perchlets were retained in the 30-mm square codend. This results in near indeterminacy of the selection curve because any very large value of L_{50} would fit the data almost as well. The extremely large standard errors of the parameter estimates reflect this phenomenon (Table 5).

Discussion

The results from experiment 1 showed that the cover had minimal effect on the fishing performance of the stow net. Catch structures in the covered and uncovered codends were less than 38% dissimilar and there were no significant differences detected for individual catches of the key species, including school and eastern king prawns, glassy perchlets and southern herring. The only significant difference was for pink-breasted siphonfish which, although present in very low abundance during all lifts, was retained in greater numbers when the cover was attached. Because other species similar in size (< 4 cm FL) and morphology (e.g. glassy perchlets) were not equally affected by the cover, it is unlikely that the observed anomaly was due to any changes in the geometry or mesh openings of the stow net. One possible explanation is that pink-breasted siphonfish were influenced by some sort of visual stimuli associated with the cover and were reluctant to pass through the meshes in the codend (Wileman et al., 1996; Dahm et al., 2002). It should also be noted that the apparently significant difference could have arisen due to the effect of multiple comparisons. It could be argued that Table 3 effectively contains five independent tests of the gear effect (for school prawns, king prawns, glassy perchlets, southern herring, and pink-breasted siphonfish) and so to preserve an overall type I error rate of 5%, that a Bonferroni corrected P value of 0.05/5 = 0.01 should be used to test each individual effect. The P value for the gear effect on catches of pink-breasted siphonfish was 0.012, and therefore not quite significant at the required level. This result suggests that any difference between the covered and uncovered codends was small, particularly relative to the between-haul variability occurring among different nights. Here, the ability to anchor the cover allowed it to be rigged to cause minimal interference with the stow net. This configuration will not be possible for towed gears and so there is a much greater potential for species-specific interactions between the covers and trawls (Wileman et al., 1996), and therefore a need to perform at least some check of the cover effect.

As with previous studies done in other prawn fisheries (e.g. Tokai et al., 1990; Thorsteinsson, 1992; Broadhurst et al., 2004), experiment 2 showed that the conventional diamond-mesh codend was virtually non-selective for the targeted penaeids, although the parameter estimates should be treated with caution. While Broadhurst et al. (2004) demonstrated that 20-mm square-mesh codends significantly improved size selectivity for the targeted school prawns in the Clarence River trawl fishery, there was no reliable evidence to indicate such an improvement in the current study. This disparity is primarily a result of the differences in the sizes of penaeids encountering the gears during the two studies, with sufficient numbers of small prawns (i.e. < 10-mm CL) caught during the trawl experiment enabling the generation of reliable selection curves (Broadhurst et al., 2004). Although the lack of small prawns caught during the current study meant that the 20-mm square codend was ineffective at improving the selectivity of school prawns, it was demonstrated to improve the size selectivity of eastern king prawns and glassy perchlets, and significantly reduce bycatch.

Simply by increasing the lateral mesh openings in the codend, the experimental 30-mm square codend reduced the overall retention of bycatch and increased the L_{50} for both penaeid species, therefore increasing the overall selectivity of the stow net. The increase in L_{50} for school prawns was, however, accompanied by a large SR, indicating an unacceptable loss of target-sized prawns. This latter result can be attributed to the knotted meshes and relatively thin polyethylene twine used in their construction. Considerable knot slippage was observed and, by the end of experiment 2, many of the meshes were elongated, which probably allowed prawns to escape over a wide range of sizes.

Although few small school prawns (i.e. less than approx. 15 mm CL) encountered the gear during the present study, the size-selection models indicate that an examination of the utility of square-shaped mesh of intermediate mesh sizes (e.g. 23- to 27-mm mesh hung on the bar) could be warranted, providing these meshes are made from knotless polyamide netting (i.e. the same material used to construct the 20-mm square codend). If the SRs are found to be lower than that of the 30-mm square codend used in the present study, codends made from these intermediate square-mesh sizes should retain acceptable proportions of target-sized school prawns, but allow smaller conspecifics and juvenile eastern king prawns to escape.

Any reduction in the fishing mortality of juvenile eastern king prawns could positively benefit the NSW oceanic prawn-trawl fishery, which targets subadult and adults (i.e. 20- to 60-mm CL – Glaister et al., 1987) of this species. Although juvenile eastern king prawns only represented 1% of the total catch of prawns during the present study, at times they occur in large numbers throughout the various stow-net fisheries in NSW. Owing to their small size, in the Clarence River they often are combined and sold with school prawns at a substantially lower value than those caught offshore. The results from experiment 2 and Broadhurst et al. (2004) indicate that 20- and 30-mm mesh hung on the bar selects eastern king prawns at slightly greater L_{50}s than school prawns. Because this is probably due to inter-specific morphological differences (Broadhurst et al., 2004), comparatively more juvenile king prawns than school prawns are likely to escape from intermediate sizes of square mesh.

Further examination of intermediate sizes of square mesh would probably also augment the reduction of non-penaeid bycatch and in particular, those small individuals of non-commercial fish species with low dorsal profiles such as whitebait, pink-breasted siphonfish, gobies and some glassy perchlets caught during both experiments. Although the bycatches of commercially-important species of fish from NSW stow nets normally are quite low and not considered to negatively impact on other fisheries (Andrew et al., 1995), any ancillary reduction in total bycatch associated with modifications designed to improve selectivity for the targeted penaeids would be a positive development towards sustainable commercial fishing practices.

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Table 1. Total numbers caught during experiment 1 and 2 for all species (or groups), excluding additional replicate sets used for size-selectivity analyses (see Methods section). *, denotes commercially- and/or recreationally-important species.

Family	Scientific name	Common name	Exp. 1	Exp. 2
Crustaceans				
Penaeidae	*Metapenaeus macleayi*	School prawn*	5,133	18,960
	Penaeus plebejus	Eastern king prawn*	82	520
	Penaeus monodon	Giant tiger prawn*	1	0
Palaemonidae	*Macrobrachium* sp.	Rock prawn*	4	2
Teleosts				
Ambassidae	*Ambassis* spp.	Glassy perchlets	398	914
Anguillidae	*Anguilla reinhardti*	Long-finned eel*	0	4
Apogonidae	*Siphamia roseigaster*	Pink-breasted siphonfish	59	6
Bothidae	*Pseudorhombus arsius*	Large-toothed flounder*	0	1
Callionymidae	*Foetorepus calauropomus*	Common stinkfish	0	1
Carangidae	*Pseudocaranx dentex*	Silver trevally*	0	8
	Scomberoides commersonianus	Queenfish*	0	1
Chaetodontidae	*Selenotoca multifasciata*	Old maid	1	2
Clupeidae	*Herklotsichthys castelnaui*	Southern herring*	124	1,557
	Hyperlophus vittatus	Whitebait	26	12
Engraulididae	*Engraulis australis*	Australian anchovy	0	14
Gerreidae	*Gerres subfaciatus*	Silver biddy*	5	60
Gobiidae	Mixed spp.	Gobies and gudgeons	2	158
	Arenigobius bifrenatus	Bridled goby	0	27
Hemiramphidae	*Arrhamphus sclerolepis*	Snub-nosed garfish*	4	3
	Hyporhamphus regularis	River garfish*	4	29
Monodactylidae	*Monodactylus argenteus*	Diamond fish	15	1
Mugilidae	*Liza argentea*	Flat-tail mullet*	1	3
	Mugil cephalus	Sea mullet*	2	3
	Valamugil georgii	Fan-tail mullet*	0	2
Platycephalidae	*Platycephalus fuscus*	Dusky flathead*	0	1
Plotosidae	*Plotosis lineatus*	Striped catfish	2	0
Pomatomidae	*Pomatomus saltatrix*	Tailor*	0	1
Scorpaenidae	*Centropogon australis*	Fortescue	2	56
	Notesthes robusta	Bullrout	0	9
Sillaginidae	*Sillago ciliata*	Sand whiting*	0	6
Soleidae	*Aseraggodes macleayanus*	Narrow-banded sole	0	3
Sparidae	*Acanthopagrus australis*	Yellowfin bream*	2	6
	Rhabdosargus sarba	Tarwhine*	0	1
Terapontidae	*Pelates sexlineatus*	Eastern striped trumpeter*	1	0
Tetraodontidae	*Tetractenos glaber*	Smooth toadfish	1	1

Table 2. Experiment 1: summaries of the mean number (± SE) caught per 45-min set (n = 12) and cumulative % of the main species in order of their contribution to dissimilarity for the covered and uncovered stow-net codend (average dissimilarity = 37.09%).

Species	Covered stow-net codend		Uncovered stow-net codend		Cumulative percentage
School prawn	208.08	(36.4)	197.00	(49.61)	85.04
Glassy perchlets	13.42	(2.07)	12.00	(2.71)	90.95
Eastern king prawn	2.90	(0.96)	3.17	(0.75)	93.16
Southern herring	4.08	(0.68)	3.83	(0.85)	95.26
Pink-breasted siphonfish	3.25	(0.67)	1.25	(0.39)	97.16
Whitebait	0.17	(0.17)	1.67	(1.40)	97.74
Diamond fish	0.58	(0.22)	0.67	(0.43)	98.26

Table 3. Experiment 1: summaries of F ratios from two-factor ANOVA comparing catches from the covered and uncovered stow net codend. Three replicate lifts of the two gear configurations were completed on each of four nights. Data were ln(x+1) transformed with the exception of glassy perchlets, whose data were not transformed due to heteroscedasticity of the transformed data. 'Pld' indicates that the F ratio for the interaction term was non-significant at P < 0.25, and the sums of squares and df pooled with the residual. ** P < 0.01; * P < 0.05.

Source of variation	df	Wt of school prawns	No. of eastern king prawns	Wt of total bycatch	No. of total bycatch
Gear configuration (G)	1	0.19	0.17	0.29	0.63
Nights (N)	3	3.72*	0.93	0.74	6.82**
G x N	3	Pld	Pld	Pld	1.86
Residual	16				
Source of variation	df	No. of glassy perchlets	No. of southern herring	No. of pink-breasted siphonfish	
Gear configuration (G)	1	0.15	0.69	7.68*	
Nights (N)	3	3.03	3.89*	0.56	
G x N	3	1.52	Pld	Pld	
Residual	16				

Table 4. Experiment 2: summaries of F ratios from a) three-factor and b) one-factor ANOVA comparing the proportions of catches escaping from three treatment codends set twice each night over four nights during two consecutive lunar periods (between the last quarter and new moon). 'Pld' indicates that the F ratio for the interaction term was non-significant at $P < 0.25$, and the sums of squares and df were pooled with the appropriate residual. All data were $\sin^{-1}(\sqrt{x})$ transformed. ** $P < 0.01$; * $P < 0.05$.

a) Source of variation	df	Wt of total prawns	No. of school prawns	Wt of total bycatch	No. of total bycatch
Codends (C)	2	4139.20**	899.97**	5.52**	31.14**
Moons (M)	1	0.04	0.03	0.44	15.87**
C x M	2	0.01	0.03	Pld	Pld
Nights(Moons) (N(M))	6	Pld	Pld	Pld	Pld
C x N(M)	12	2.13	2.05	Pld	Pld
Residual	24				

b) Source of variation	df	No. of eastern king prawns	df	No.of glassy perchlets
Codends	2	88.96**	2	43.86**
Residual	21		31	

Table 5. Experiment 2: carapace length and fork length (mm) at 50% probability of retention (L_{50}) and selection ranges (SR) for school and eastern king prawns and glassy perchlets respectively, caught in the 30-mm diamond, 20-mm square and 30-mm square codends. Standard errors are given in parentheses. *, estimates not considered reliable due to lack of data.

Codend	Parameter	School prawns	Eastern king prawns	Glassy perchlets
30-mm diamond	L_{50}	8.46 (1.65)	8.08* (5.31)	33.57 (4.01)
	SR	3.55 (0.86)	5.11* (5.24)	9.83 (4.84)
20-mm square	L_{50}	9.68 (1.17)	11.68 (1.24)	46.44 (2.11)
	SR	2.58 (0.64)	3.03 (1.83)	10.39 (4.45)
30-mm square	L_{50}	16.05 (0.18)	16.59 (1.55)	98.29*(149.60)
	SR	4.76 (0.57)	3.35 (2.44)	39.76*(108.56)

Captions to Figs

Figure 1. Configuration of the A) stow net and B) codend cover used in the experiments.

Figure 2. Schematic diagram of the A) 30-mm diamond, B) 20-mm square and C) 30-mm square codends. All codends are 3 m in length. N, normals; T, transversals; B, bars.

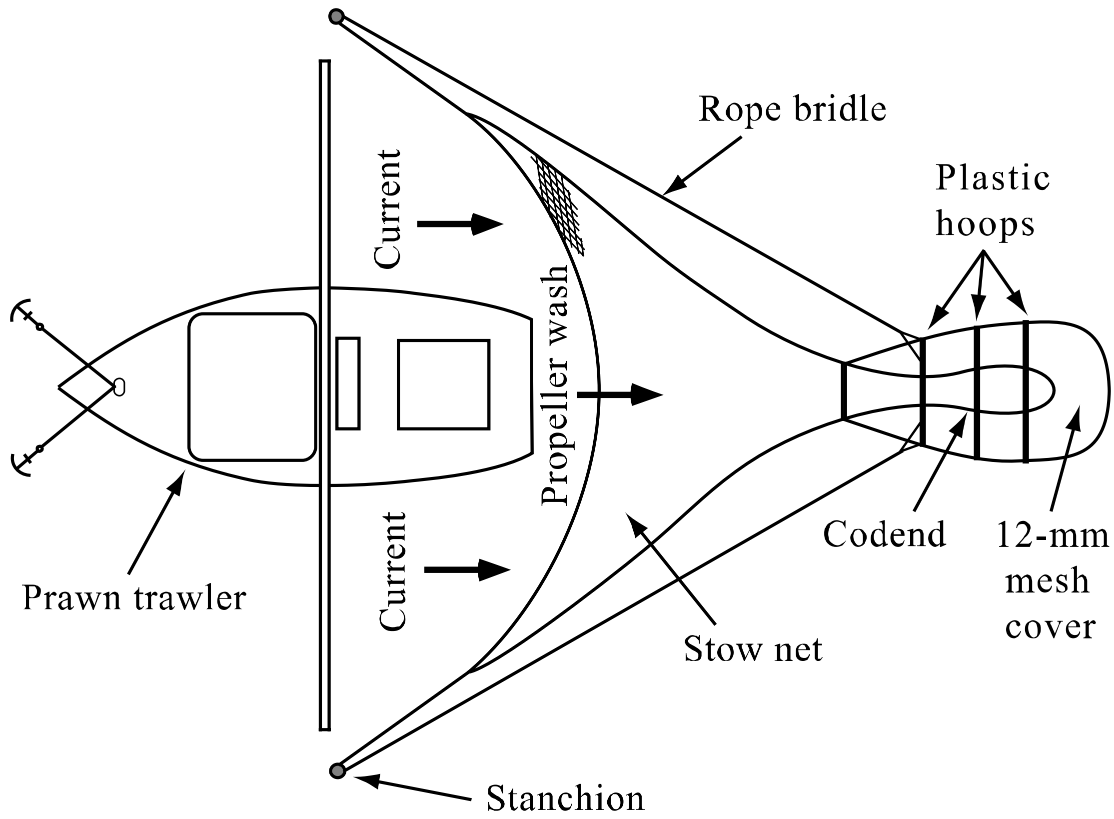
Figure 3. Two-dimensional ordination for the numbers of all species retained in the covered (●) and uncovered (○) stow-net codend during experiment 1 (n = 12).

Figure 4. Mean proportion (+ SE) of catches escaping from the three treatment codends tested in experiment 2 (n = 16), for the A) weight of total prawns, numbers of B) school and C) eastern king prawns, D) weight and E) number of bycatch, and H) number of glassy perchlets. 30-d, 20-s and 30-s refer to 30-mm diamond, 20-mm square and 30-mm square codends respectively. Symbols < and = indicate direction of significant differences detected in SNK tests (P = 0.05).

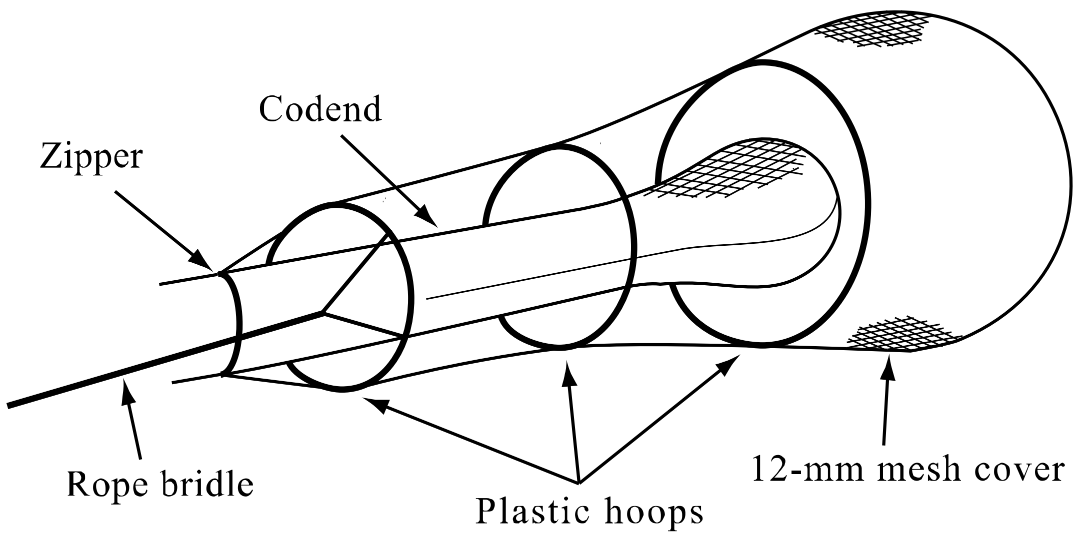
Figure 5. Logistic selection curves for the three codends tested during experiment 2, and size-frequency curves for all prawns caught during sets used for size-selectivity analyses, for A) school and B) eastern king prawns. 30-d, 20-s and 30-s refer to 30-mm diamond, 20-mm square and 30-mm square codends respectively. *, curve not considered reliable due to lack of data.

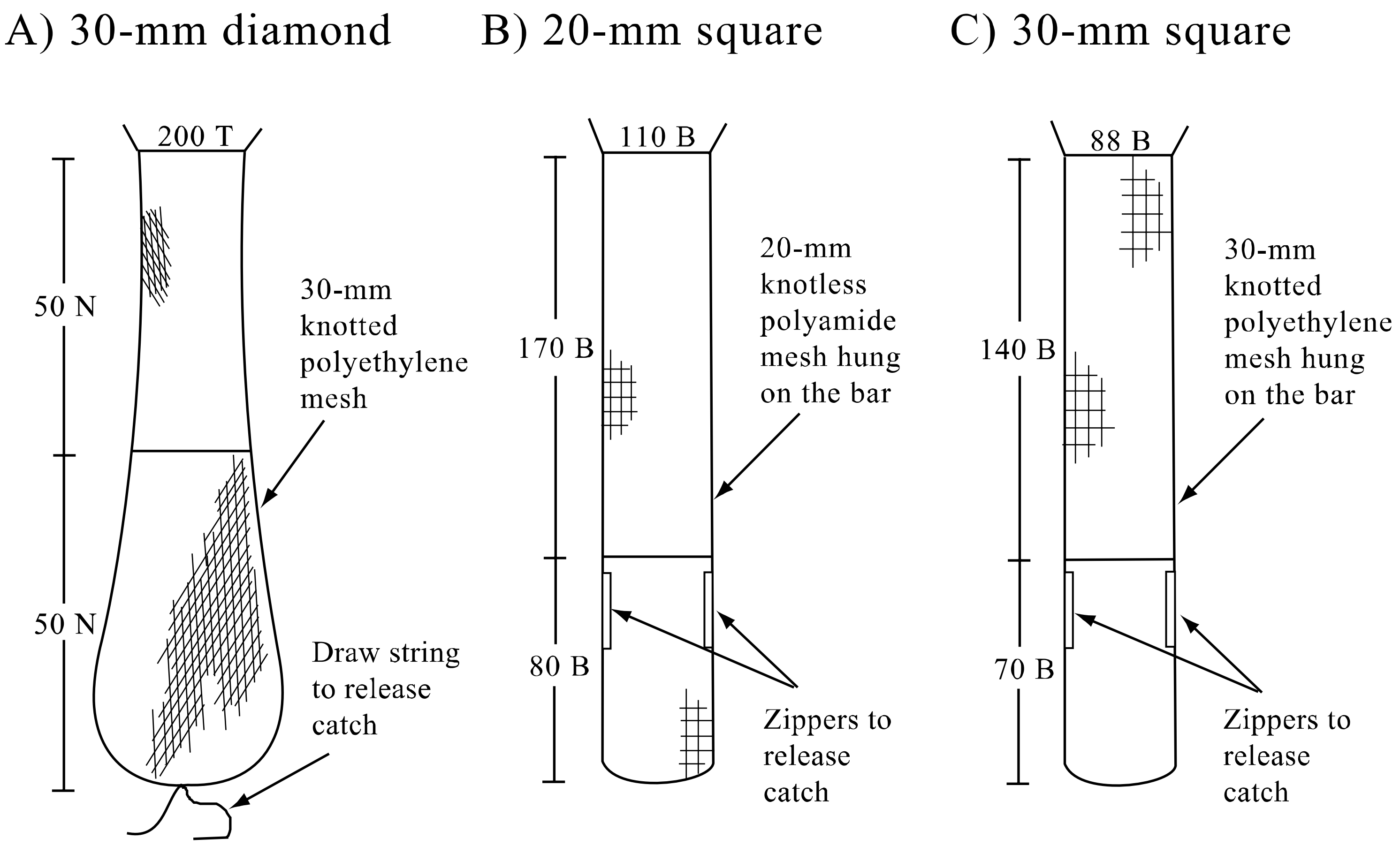
Figure 6. Logistic selection curves for glassy perchlets caught in the three codends tested during experiment 2, and size-frequency curve for all glassy perchlets caught during sets used for size-selectivity analyses. 30-d, 20-s and 30-s refer to 30-mm diamond, 20-mm square and 30-mm square codends respectively. *, curve not considered reliable due to lack of data.

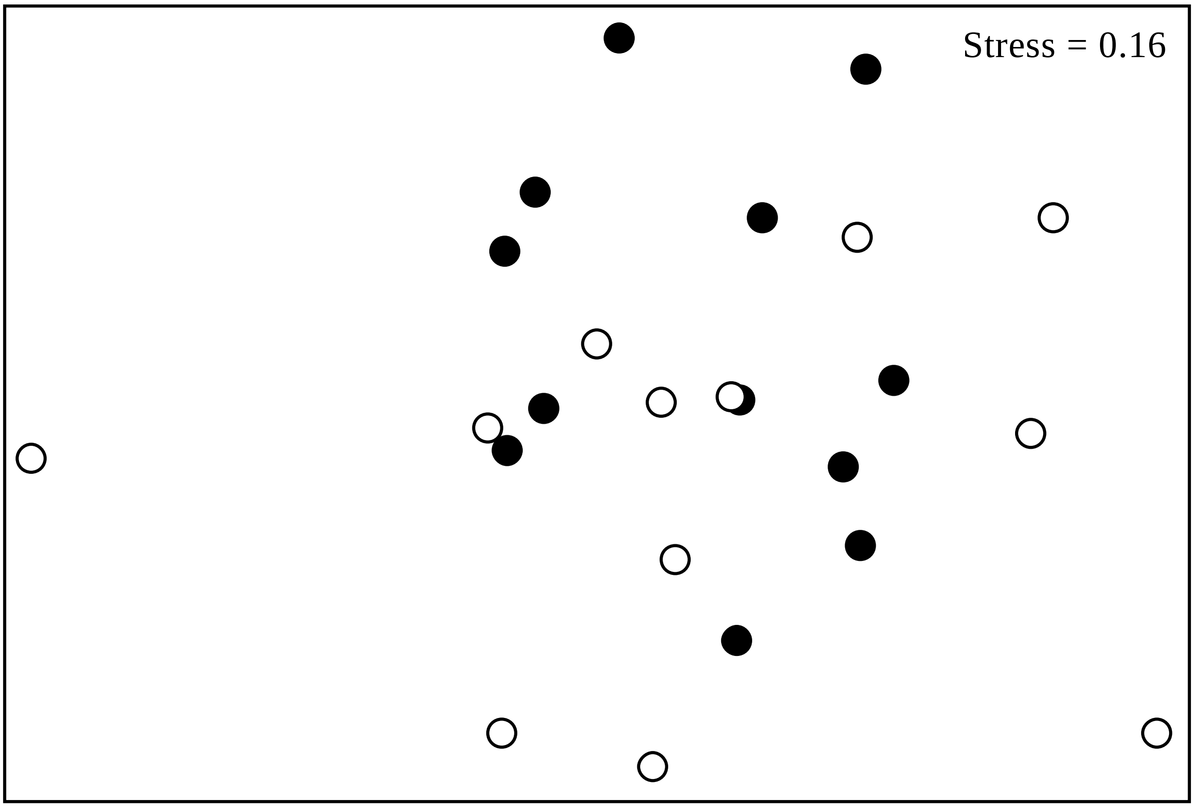
A) Stow net

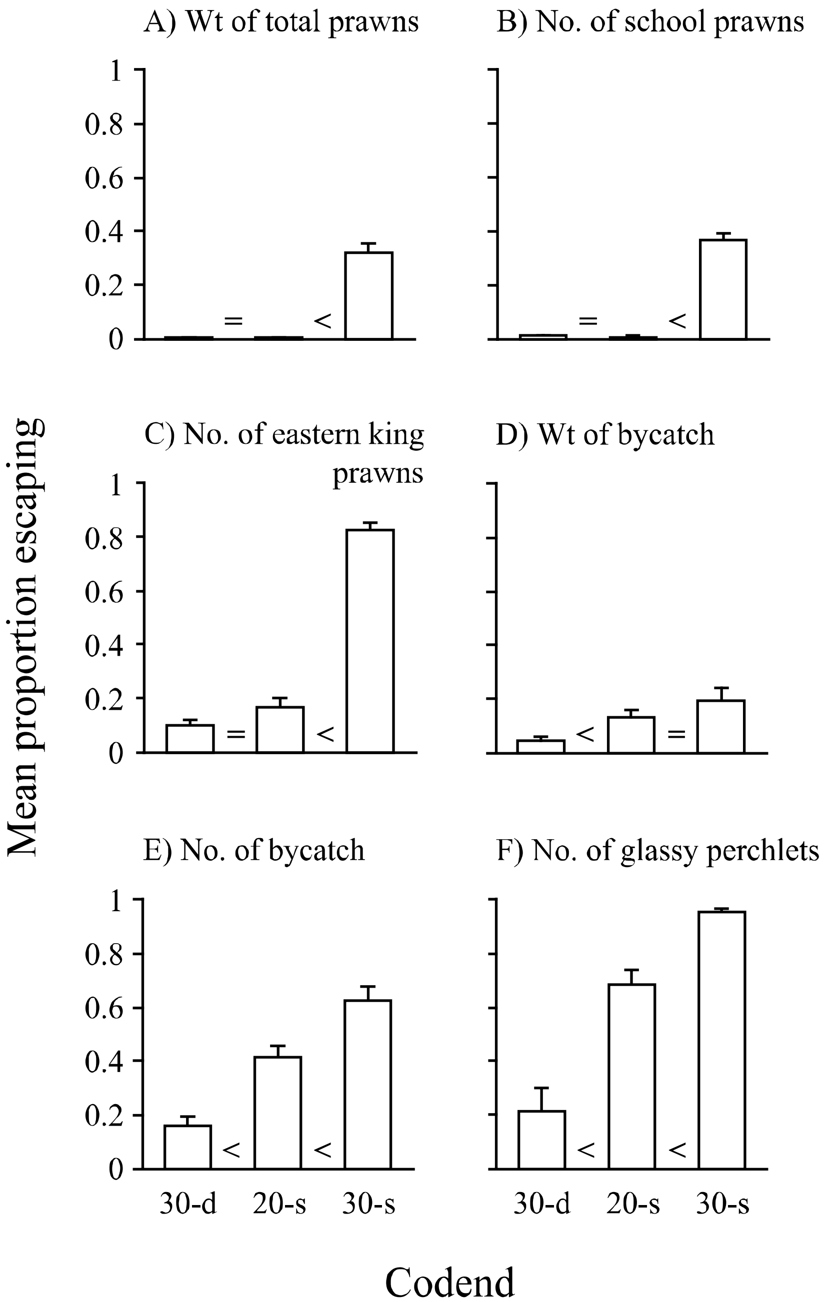


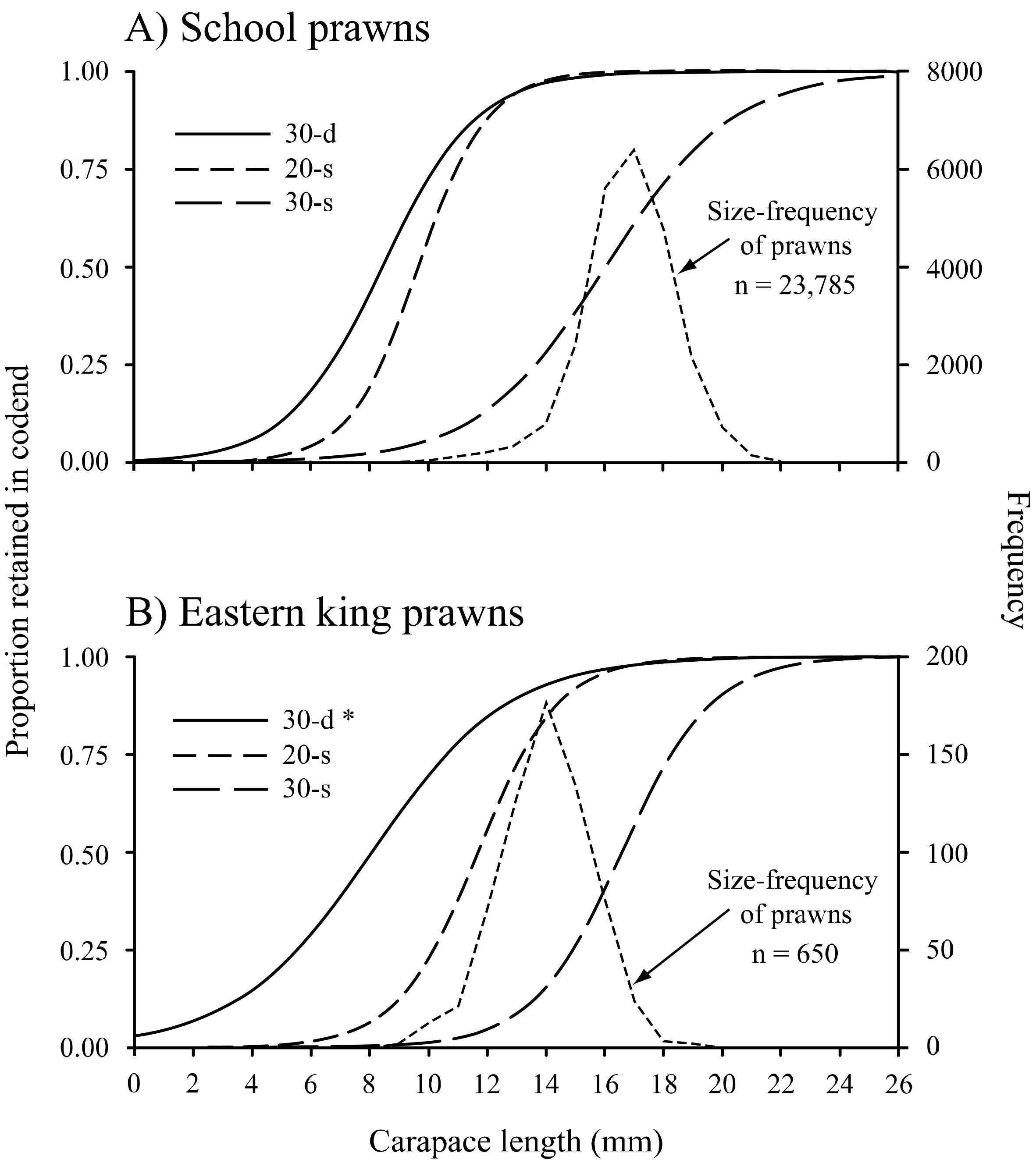
B) Codend cover

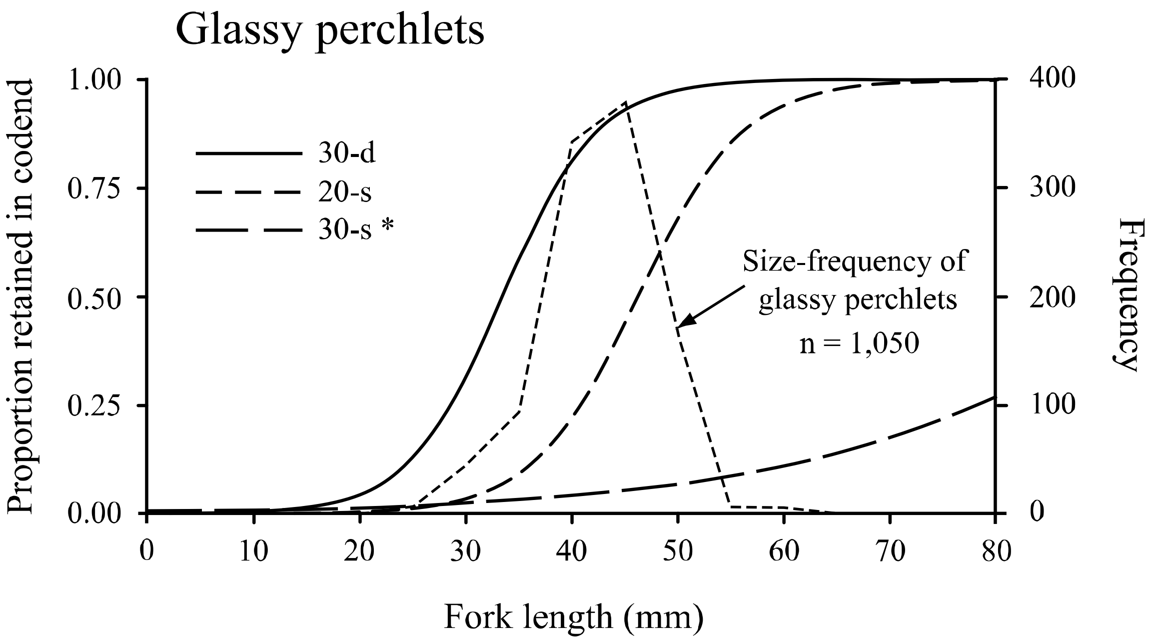



A) 30-mm diamond
B) 20-mm square
C) 30-mm square
200 T
50 N
50 N
30-mm knotted polyethylene mesh
Draw string to release catch
110 B
170 B
80 B
20-mm knotless polyamide mesh hung on the bar
Zippers to release catch
88 B
140 B
70 B
30-mm knotted polyethylene mesh hung on the bar
Zippers to release catch


Stress = 0.16


A) Wt of total prawns
B) No. of school prawns
C) No. of eastern king prawns
D) Wt of bycatch
E) No. of bycatch
F) No. of glassy perchlets
Mean proportion escaping
0
0.2
0.4
0.6
0.8
1
=
<
30-d
20-s
30-s
Codend


A) School prawns
30-d
20-s
30-s
Size-frequency of prawns n = 23,785
B) Eastern king prawns
30-d *
20-s
30-s
Size-frequency of prawns n = 650
Proportion retained in codend
Frequency
Carapace length (mm)
1.00
0.75
0.50
0.25
0.00
8000
6000
4000
2000
0
200
150
100
50
0
2
4
6
8
10
12
14
16
18
20
22
24
26


Glassy perchlets
1.00
0.75
0.50
0.25
0.00
Proportion retained in codend
30-d
20-s
30-s *
Size-frequency of glassy perchlets n = 1,050
400
300
200
100
0
Frequency
0
10
20
30
40
50
60
70
80
Fork length (mm)

Appendix 12 - Broadhurst, M.K., Wooden, M.E.L., Young, D.J. and Macbeth, W.G. 2004. Selectivity of penaeid trap nets in south-eastern Australia. Sci. Mar. 68(3): 445-455.

SCI. MAR., 68 (3): 445-455 SCIENTIA MARINA 2004

Selectivity of penaeid trap nets in south-eastern Australia*

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SUMMARY: Two experiments were done to estimate the selectivity of commercial and modified trap-net configurations in New South Wales (NSW), southeastern Australia. In the first experiment, a commercial trap net made entirely from 25 mm mesh and designed for use in shallow water was alternatively fished with a fine-meshed (9.5 mm netting) trap net (used as a control). In the second experiment, two trap-net configurations designed for use in deeper water and comprising the same anterior section (made from 25 mm mesh), but with different bunts made from (i) the conventional 25 mm mesh and (ii) 31 mm mesh were alternately fished against the control. Both of the conventional trap nets (comprising 25 mm mesh throughout) had low amounts of bycatch and similarly selected eastern king *Penaeus plebejus*, greasyback *Metapenaeus bennettae* and school prawns *Metapenaeus macleayi* across narrow selection ranges (< 3.4 mm) and at 50% retention lengths (between 18.53 and 21.50 mm) that were larger than the average commercially-accepted sizes (15-17 mm CL). Analyses of the selectivities and relative efficiencies of the trap-net configurations comprising the 25 and 31 mm bunts showed no benefit, in terms of maintaining prawn catches and reducing unwanted bycatch, associated with increasing mesh size in these gears. The utility of trap nets for selectively harvesting penaeids is discussed. We conclude that this type of fishing gear appears to have few deleterious impacts.

Key words: Penaeids, selectivity, trap net, fishing gear, south eastern Australia.

RESUMEN: SELECTIVIDAD DE LAS NASAS DE RED PARA PENEIDO EN EL SUDESTE DE AUSTRALIA. – Con el fin estudiar la selectividad de nasas comerciales y la configuración de nasas con redes modificadas, se realizaron dos experimentos en el New South Wales (NSW), al sudeste de Australia. En el primer experimento, se comparó una nasa comercial hecha con malla de 25 mm y diseñada para ser usada en aguas poco profundas con una de 9,5 mm usada como control. En el segundo experimento se utilizaron dos nasas diseñadas para aguas profundas las cuales tenían la misma sección anterior de 25 mm de malla, pero con distintos sacos hechos de (i), malla convencional de 25 mm y (ii), malla de 31 mm. Ambas nasas convencionales (de 25 mm de malla), pescaron poca cantidad de especies acompañantes y seleccionaron de manera similar al langostino *Penaeus plebejus*, *Metapenaeus macleay* y *Metapenaeus bennettae* a través de una sección estrecha con menos de <3,4 mm de rango de variación y con un 50% de retención entre las longitudes de 18,53 y 21,50 mm CL. Los análisis de selectividad y eficiencia relativa de las configuraciones de nasas de red comprendiendo 25 y 31 mm de saco no mostraron ningún beneficio en términos de gestión para las capturas de langostinos, pero sí reducción de las especies acompañantes no deseadas al aumentar la malla de estos artes. Se discute la utilidad de las nasas de red para la selectividad en los desembarcos de peneidos. Concluimos que este tipo de arte de pesca tiene poco impacto nocivo en la pesquería.

Palabras clave: Penaeids, selectividad, nasa de red, arte de pesca, sudeste australiano.

INTRODUCTION

Penaeids form the basis of several important commercial fisheries in New South Wales (NSW), Australia that have a total value of more than $A26 M per annum. Catches include 6 species, although eastern king *Penaeus plebejus*, school *Metapenaeus macleayi* and greasyback prawns *Metapenaeus bennettae* account for more than 98% of the total annual production (approx. 2000 t). These 3 species are

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targeted throughout their distributions across nearshore and estuarine habitats (Coles and Greenwood, 1983) using a combination of static (stow and trap nets) and towed (otter trawls and seines) fishing gears.

All of these gears are managed by a range of input controls that include limits on their dimensions, effort, methods and areas of operation and minimum and maximum legal mesh openings (for a definition, see Ferro and Xu, 1996). These legal mesh sizes vary between 40 and 45 mm in the codends of otter trawls, 30 and 36 mm throughout seines and stow nets and 25 and 36 mm in trap nets. The use of these small-meshed gears throughout habitats that are typically characterised by diverse assemblages and abundances of small fauna (Bell *et al.*, 1988; Gray *et al.*, 1996) is of considerable concern and has resulted in several quantitative studies of catches (e.g. Gray *et al.*, 1990; Andrew *et al.*, 1995; Liggins and Kennelly, 1996; Liggins *et al.*, 1996; Kennelly *et al.*, 1998; Gray, 2001). These studies revealed that at some locations and times, penaeid fishing gears, and especially otter trawls, retain incidental catches (collectively termed 'bycatch' *sensu* Saila, 1983) that often comprise juveniles of commercially-important teleosts, molluscs and crustaceans, including small, unwanted conspecifics (< approximately 15 mm carapace length - CL; Broadhurst *et al.*, 2004) of the targeted species. Concerns over the mortality of these organisms and the potential impacts on their stocks have resulted in successful attempts at improving gear selectivity. The majority of this work has concentrated on otter trawls used throughout various marine (e.g. Broadhurst and Kennelly, 1997) and estuarine (Broadhurst and Kennelly, 1994; 1996; Broadhurst *et al.*, 2004) fisheries. Considerably less attention has been directed towards assessing static gears (but see Macbeth *et al.*, 2004) and no work has been done on trap nets.

Trap netting in NSW involves up to 95 operators who are permitted to fish in 12 coastal lakes and lagoons, although more than 40% of the effort is concentrated at Tuggerah Lakes (33°19'S, 151°30' E). Fishing mostly occurs at night and between the last and first quarter phases of the moon. All of the trap-net configurations used in NSW are similar, and consist of a wall of 25 mm netting (i.e. the minimum legal mesh size for this gear) up to 140 m in length. The width of this wall of netting varies from approximately 1 to 6 m, depending on the depths fished. For example, trap nets used at sites that are shallow and with slow currents typically have a narrow (e.g. 1 m) anterior section made from stiff, positively-buoyant polyethylene (PE) netting, which helps to maintain net distension during fishing (Figs 1A and 2B). In contrast, trap nets used in deeper (e.g. > 2 m), faster-flowing water have wide transverse sections (i.e. up to approx. 6 m) of negatively-buoyant polyamide (PA) netting throughout.

Trap nets are set by attaching one end to a vertical stanchion near the shore and the other end to the horizontal gunwale of a dory anchored on the lake (Fig. 2A and B). Currents cause the anterior section of the netting to distend and assume a parabolic shape, effectively trapping migrating penaeids and directing them along the wall of netting towards the horizontally-orientated bunt (at the dory). Fishers facilitate this movement of catch by regularly lifting and hauling sections of the headline and footrope over a second dory so that it passes underneath the trap net and the catch is progressively rolled towards the bunt (Fig. 2C).

Anecdotal information from fishers suggests that trap nets have low amounts of bycatch and are more selective than other gears used to target penaeids in NSW. However, there are no formal estimates of the selectivity of the various configurations or of the effects of any modifications on their performance. Our aims in the present work were to address this lack of information by (i) quantifying the selectivity of the most common configurations used and (ii) examining the relative efficiency of a larger mesh size in the bunt of one of these gears.

MATERIAL AND METHODS

This study was done at commercial trap net sites in Tuggerah Lakes between the last and first quarter moon phases of January and February 2003. All sites ranged in depth from 0.5 to 3 m and encompassed a combination of sloping sand and mud bottoms with patches of seagrass.

Trap-net configurations examined

Four trap-net configurations were used at these sites. All trap nets were made from dark netting that had a maximum stretched depth of approx. 6 m and hung at 50% on buoyed headlines and weighted footropes, 140 m in length (Fig. 1). The first configuration, termed the 25 mm PE/PA trap net, represented those commercial designs that are typically

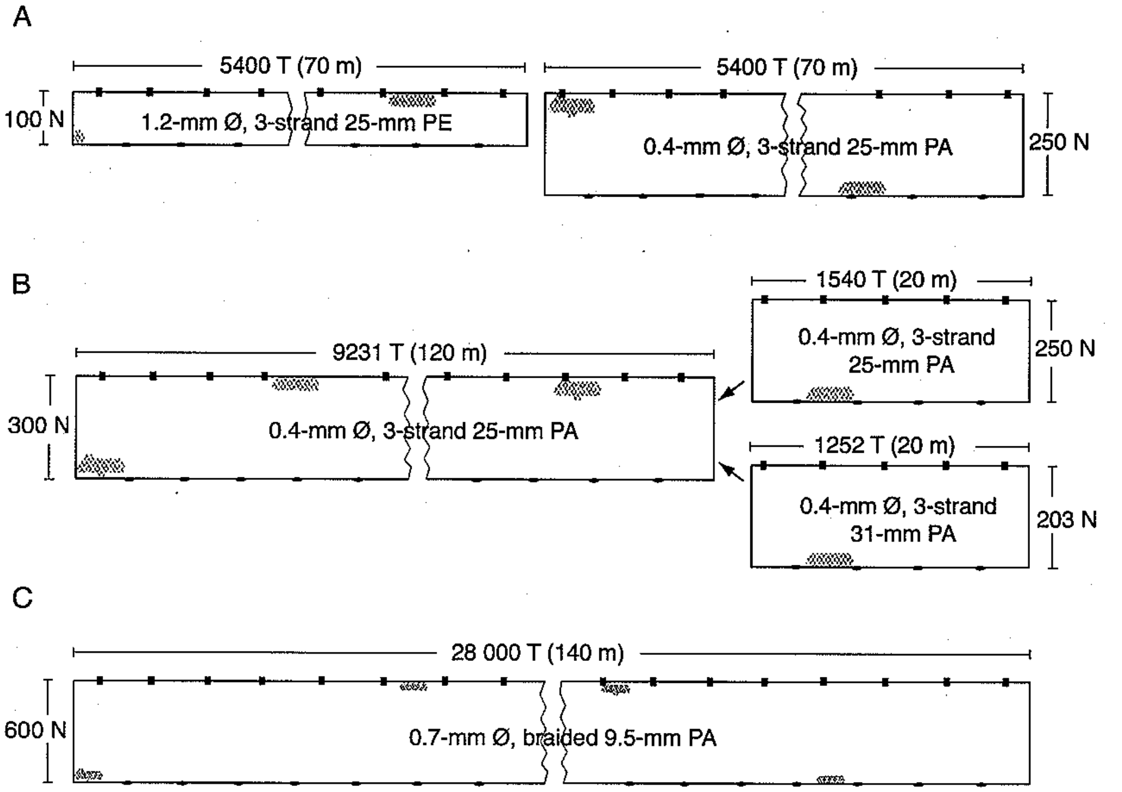

FIG. 1. – Diagrammatic representation of the A) 25 mm PE/PA, B) 25- and 31 mm bunt and C) control trap-net configurations (m: metres; N: normals; T: transversals: PA: polyamide; PE: polyethylene; ş: diameter).

fished at shallow sites (e.g. < 1 m deep—see discussion above) and comprised two sections that were each 70 m in length and made from 100 meshes (normal direction - N) of 25 mm knotted PE (approx. 1.2 mm diameter – Ş, 3-strand twisted twine) and 250 N of 25 mm knotted PA (approx. 0.4 mm Ş, 3-strand twisted twine) netting respectively (Fig. 1A). The second and third trap-net configurations had the same anterior section (300 N of 25 mm knotted, PA netting—i.e. the same material as that used above—120 m in length), but different bunts. Both bunts were 20 m long, approx. 6 meters wide and made from 0.4 mm Ş, 3-strand twisted PA twine, but with mesh sizes that were 25 and 31 mm respectively (Fig. 1B). These bunts and the anterior section of the trap net were rigged with zippers (Buraschi S146R, 6 m in length) to facilitate their attachment. The 25 mm bunt attached to the anterior section described above represented the majority of the commercial trap-net configurations used throughout NSW (Fig. 1B). The larger-meshed, 31 mm bunt attached to the anterior section represented a modified and previously untested trap-net configuration. We hypothesised that this larger-meshed bunt would increase the size selection of the trap net for penaeids and small individuals comprising the bycatch. The fourth trap net was termed the control, and comprised 600 N (i.e. approximately 6 m stretched depth) of 9.5 mm knotless PA netting (0.7 mm Ş, braided twine) throughout (Fig. 1C).

Experimental design

All fishing was done at night (between 20:00 and 03:00) and according to normal commercial procedures. During all sets, the headline and footrope of the anterior end of the particular trap-net configuration being used (see below for details) were secured to a staked stanchion and the net set from a dory along the bottom of the lake in a straight line (Fig. 2A). The headline and footrope of the bunt were horizontally secured to a second dory that was

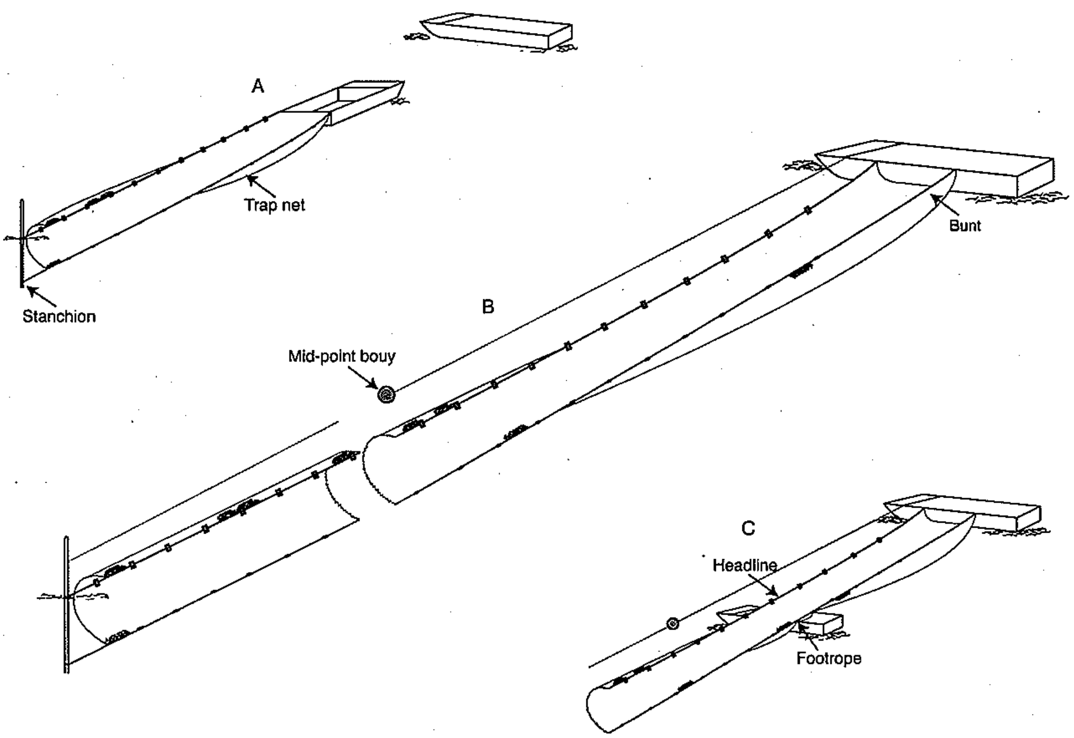

FIG. 2. – Diagrammatic representation of A) the method for setting the trap nets, B) the traps nets during fishing and C) using a dory to progressively concentrate the catch towards the bunt.

anchored in position (Fig. 2A and B). To mark the middle of the trap net, approx. 140 m of 4 mm Ş, PE rope was attached between the stanchion and the second dory, and a large float was clipped at 70 m (Fig. 2B). Each trap net was left to soak for 25 minutes, after which the first dory returned to the middle of the gear and the headline and footrope were lifted onboard (Fig. 2C). Two fishers simultaneously hauled the headline and footrope so that the dory passed under the trap net and the catch was concentrated towards the bunt and then into the first dory (Fig. 2C). The trap net was then removed from the lake and the next configuration was set.

Using this fishing method, two experiments were done during consecutive phases of the new moon. In the first experiment, the 25 mm PE/PA trap net was alternatively fished against the control at a shallow (< 1 m) commercial trap-net site. We attempted between 2 and 3 replicate, alternate 25 min sets of the treatment and control trap net on each night and completed a total of 15 balanced sets over 6 nights. In the second experiment, the 25 and 31 mm bunts were alternatively zippered to the anterior 25 mm PA trap-net section and fished against the control at two sites—which were determined randomly and/or according to the prevailing weather conditions (i.e. the direction and strength of wind and waves) each night. Over 8 nights, we attempted two replicate nightly sets of each trap-net configuration and successfully completed a total of 14 balanced replicates.

Data collected from all trap-net sets included: the number and weight of total prawns; the numbers, weights and all carapace lengths (CL to the nearest 1 mm) of greasyback, eastern king and school prawns; the weight of total bycatch; the numbers of all fish and their fork lengths (FL to the nearest 5 mm); and the numbers of all other species. Where it was not possible to identify individual species, these were grouped at the levels of genus or family.

Statistical analyses

Data from the two experiments were analysed in different detail. Attempts were made at modelling and comparing the selectivity of all treatment trap nets for the key species encountered in both experiments. In addition, because the control was alternately fished against a commercial and modified, larger-meshed trap-net configuration during experiment 2, specific hypotheses concerning gear-related effects on catches were examined using multivariate and univariate analyses (detailed below).

For both experiments, the size-frequencies of individuals of species caught in sufficient quantities (at least 100 individuals from each trap net configuration) were combined across all tows for the control and each of the treatment trap nets. Parametric selection curves (logistic and Richards) were fitted to these data using maximum likelihood (Millar and Fryer, 1999). These fits used an estimated-split SELECT model (Millar and Walsh, 1992) and were assessed by visual examination of residual plots and by comparing model deviances and associated degrees of freedom against a χ^2 distribution. The standard errors of parameter estimates (i.e. 50% retention length - L_{50} and difference in length between 25 and 75% retention lengths - selection range or SR) were adjusted according to an appropriately-derived replicate estimate of over-dispersion (Millar and Fryer, 1999). Pairwise bivariate Wald statistics were calculated using the estimated parameter vectors to test for differences between the selectivity curves for each of the treatment trap nets (Kotz *et al.*, 1982).

TABLE 1. – Scientific and common names and number (N) of organisms caught during the study.

Family	Scientific name	Common name	N
Crustaceans			
Penaeidae	*Metapenaeus macleayi*	School prawn[1,2*]	1738
	Metapenaeus bennettae	Greasyback prawn[1,2*]	1609
	Penaeus plebejus	Eastern king prawn[1,2*]	3156
Portunidae	*Portunus pelagicus*	Blue swimmer crab[1,2*]	10
	Scylla serrata	Mangrove crab[1,2*]	1
Teleosts			
Ambassidae	*Ambassis* spp.	Glassy perchlets[1,2]	2626
Anguillidae	*Anguilla reinhardti*	Long-finned eel[1,2*]	3
Antennariidae	*Antennarius striatus*	Striped angler[2]	1
Atherinidae	*Atherinomorus ogilbyi*	Hardyhead[1,2]	186
Balistidae	*Monacanthus chinensis*	Fan-bellied leatherjacket[2*]	2
	Meuschenia trachylepis	Yellow-finned leatherjacket[2*]	3
Belonidae	*Ablennes hians*	Barred long-tom[2]	3
Callionymidae	*Foetorepus calauropomus*	Common stinkfish[2]	2
Chaetodontidae	*Microcanthus strigatus*	Stripey[1,2]	10
Clupeidae	*Herklotsichthys castelnaui*	Southern herring[1,2*]	2037
	Hyperlophus vittatus	Whitebait[1,2]	1318
Dasyatididae	*Dasyatis thetidis*	Estuary stingray[1,2]	3
Diodontidae	*Dicotylichthys punctulatus*	Three-barred porcupine-fish[1,2]	11
Engraulidae	*Engraulis australis*	Australian anchovy[2]	2
Gerreidae	*Gerres subfasciatus*	Silver biddy[1,2*]	33
Gobiidae	Mixed spp.	Gobies[1,2]	393
Hemiramphidae	*Hyporhamphus regularis*	River garfish[1,2*]	167
Kyphosidae	*Girella tricuspidata*	Luderick[1,2*]	11
Monodactylidae	*Monodactylus argenteus*	Diamond fish[1,2]	81
Mullidae	*Upeneus tragula*	Bar-tailed goatfish[2]	1
Mugilidae	*Liza argentea*	Flat-tail mullet[1,2*]	9
Platycephalidae	*Platycephalus fuscus*	Dusky flathead[1,2*]	2
Plotosidae	*Plotosis lineatus*	Striped catfish[2]	1
	Cnidoglanis macrocephalus	Estuary catfish[1,2*]	2
Pomatomidae	*Pomatomus saltatrix*	Tailor[1,2*]	13
Scorpaenidae	*Centropogon australis*	Fortescue[1,2]	77
Sillaginidae	*Sillago ciliata*	Sand whiting[2*]	2
Soleidae	*Aseraggodes macleayanus*	Narrow-banded sole[1]	1
	Synaptura nigra	Black sole[2]	3
Sparidae	*Acanthopagrus australis*	Yellowfin bream[1,2*]	12
	Pagrus auratus	Snapper[1]	1
	Rhabdosargus sarba	Tarwhine[1,2*]	4
Sphyraenidae	*Sphyraenella obtusata*	Striped sea-pike[2*]	1
Tetraodontidae	*Tetractenos hamiltoni*	Common toadfish[1,2]	6
Terapontidae	*Pelates sexlineatus*	Six-lined trumpeter[1,2*]	142
Molluscs			
Loliginidae	*Photololigo etheridgei*	Broad squid[1,2]	136
	Loliolus noctiluca	Bottle squid[1,2]	25
Octopodidae	*Octopus* sp.	Octopus[1]	1

[1,2]species recorded during experiments 1 and/or 2, respectively.
*commercially and/or recreationally important species.

Using the full data set from experiment 2, non-metric multivariate analyses were used to investigate differences in the structures of catches between the trap-net configurations, following the methodologies presented by Clarke and Warwick (2001). Abundances were √ transformed and used to develop Bray-Curtis similarity matrices. Ordination of the relationships among ranks of these similarities from individual sets of the three trap-net configurations was done by multi-dimensional scaling (MDS). Two-way crossed analyses of similarity (ANOSIM) were used to test for differences in catch assemblages from the 3 trap nets over the 8 nights fishing. Significant R values from these analyses were used to group the trap nets, which were subsequently explored using SIMPER (Clarke and Warwick, 2001).

Parametric univariate analyses were used to examine differences in the catches of the key species and groups identified above among the trap-net configurations used in experiment 2. To provide balanced analyses, only nights with two replicate sets of each trap-net configuration were considered. Data were ln(x+1) transformed, tested for heterogeneous variances, and analysed by appropriate 2-factor (nights and trap nets as random and fixed factors respectively) orthogonal analyses of variance (ANOVA). To increase power for the main effects of trap nets, where the interaction term was non-significant at $P < 0.25$, it was pooled with the residual (Winer, 1971). All significant main effects of the trap net were investigated using Student-Newman-Keuls (SNK) multiple comparisons. The means for all significant interactions were graphed, but not investigated further owing to the low level of replication within nights (i.e. only two replicate sets of each trap net).

RESULTS

Thirty three families comprising more than 43 species were captured during this study (Table 1). It was not possible to distinguish between 2 and 3 species of glassy perchlets and gobies respectively, so these were grouped by genus and family.

Sufficient quantities and appropriate sizes of eastern king, greasyback and school prawns (Fig. 3)

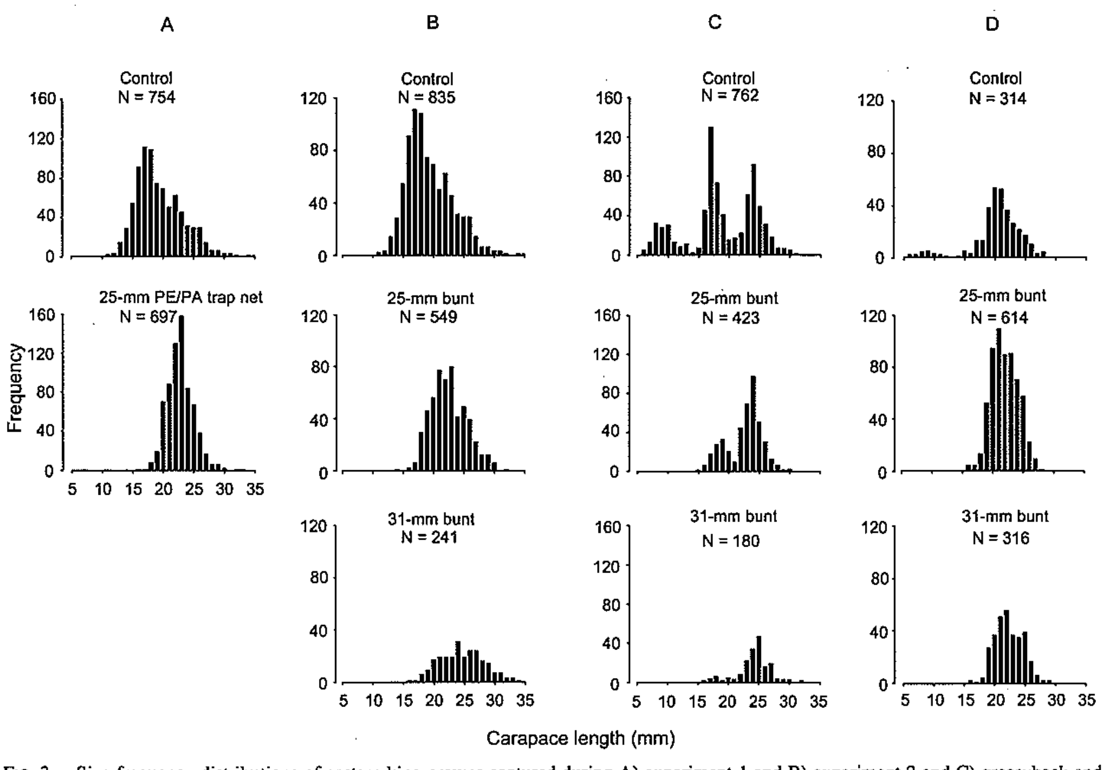

FIG. 3. – Size-frequency distributions of eastern king prawns captured during A) experiment 1 and B) experiment 2 and C) greasyback and D) school prawns captured during experiment 2.

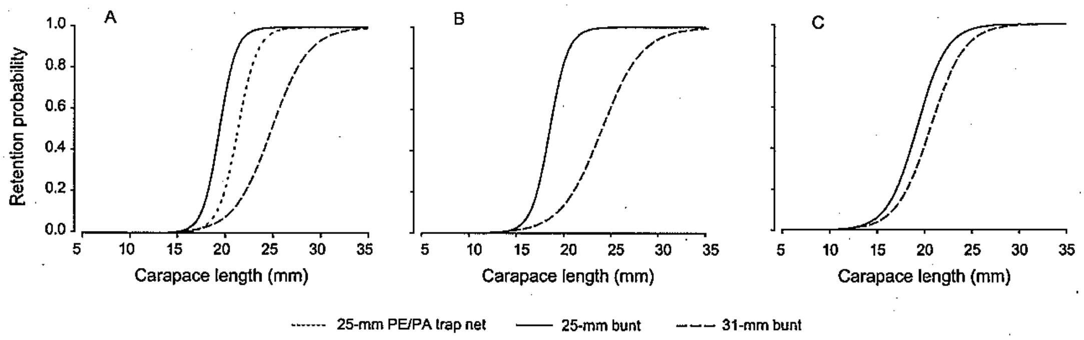

FIG. 4. – Logistic selection curves for A) eastern king, B) greasyback and C) school prawns for the various treatment trap-net configurations.

TABLE 2. – Carapace and fork lengths (mm) at 50% probability of retention (L_{50}), selection ranges (SR) and relative fishing efficiencies (p) for greasyback prawns, eastern king prawns, school prawns and southern herring from the various trap-net configurations. Standard errors are given in parentheses.

	Eastern king prawns	Greasyback prawns	School prawns	Southern herring
25-mm PE/PA trap net				
L_{50}	21.50(0.47)	–	–	76.33(4.48)
SR	2.23(0.34)	–	–	7.20(4.49)
p	0.73(0.03)	–	–	0.84(0.04)
25-mm bunt				
L_{50}	19.42(0.44)	18.53(0.30)	19.42(0.97)	–
SR	1.90(0.40)	2.09(0.38)	3.40(1.15)	–
p	0.60(0.03)	0.52(0.02)	0.75(0.04)	–
31-mm bunt				
L_{50}	24.97(1.91)	23.67(1.58)	20.70(1.46)	78.46(5.75)
SR	4.36(0.87)	4.71(0.87)	3.90(1.55)	8.12(7.30)
p	0.67(0.10)	0.48(0.07)	0.66(0.07)	0.70(0.04)

and southern herring (30-120 mm FL) were caught to enable attempts at modelling their selectivities for at least one of the treatment trap-net configurations in either experiment. A logistic model (Fig. 4, Table 2) was used in all cases because: (i) the null hypothesis for the goodness-of-fit test was not rejected ($P > 0.05$); (ii) the deviance residuals showed no clear structure; and (iii) there was no significant reduction in deviance associated with using a Richards curve.

Pairwise bivariate Wald tests detected significant differences in parameter estimates between the 25 and 31 mm bunts for eastern king and greasyback prawns, with the larger-meshed bunt selecting individuals at larger L_{50}s and across considerably greater SRs ($P < 0.01$, Fig. 4A and B, Table 2). No significant differences were detected in the estimated selection parameters for school prawns between these bunts ($P > 0.05$; Fig. 3C, Table 2). The 25 mm PE/PA trap net selected eastern king prawns at significantly greater and lower parameters than the 25 and 31 mm bunts respectively (Pairwise test $P < 0.01$, Fig. 3A, Table 2). The estimated selection parameters for southern herring were not significantly different between the 25 mm PE/PA trap net and the 31 mm bunt ($P > 0.05$, Table 2).

MDS of the abundance data from the control trap net and 25 and 31 mm bunts used in experiment 2 had a stress of 0.14 for the best two-dimensional ordination, indicating sufficient representation (Fig. 5). Catch structures were significantly different among

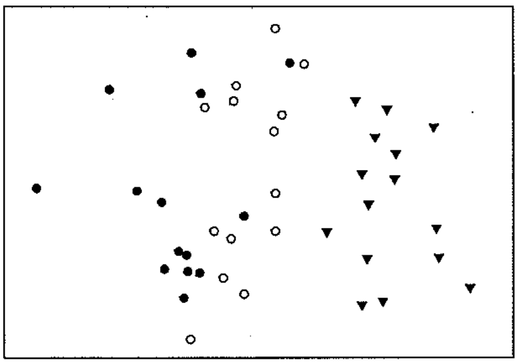

FIG. 5. – Two-dimensional ordination for the numbers of all species captured in the control and 25 and 31 mm bunts during experiment 2 (stress = 0.14; ● 31 mm bunt; ○ 25 mm bunt; ▼ control).

TABLE 3. – Summaries from SIMPER analyses of the mean number per 25-min set, % contribution and cumulative % of species contributing to > 99% of the significant dissimilarities detected between the control and treatment (25- and 31-mm bunts) trap-net configurations in experiment 2.

Species	Mean no. Control	Mean no. Treatments	% contribution	Cumulative %
King prawns	58.73	28.25	16.41	16.41
Glassy perchlets	54.47	1.04	16.11	32.52
Whitebait	66.73	0.00	14.86	47.37
Greasyback prawns	52.00	21.54	14.50	61.87
Southern herring	16.67	47.11	12.23	74.10
School prawns	20.87	33.21	9.16	83.26
Gobies	22.27	0.00	6.22	89.48
Hardyhead	7.80	1.07	2.87	92.35
River garfish	6.47	1.14	2.10	94.45
Six-lined trumpeter	1.20	4.21	1.20	95.65
Broad squid	1.93	3.21	1.09	96.74
Fortescue	3.00	0.64	0.94	97.68
Diamond fish	1.40	1.36	0.66	98.35
Silver biddy	0.07	1.14	0.45	98.80
Luderick	0.47	0.11	0.20	99.00

nights (averaged across the three trap nets—ANOSIM Global R = 0.568, $P < 0.01$) and among trap-net configurations (averaged across the 8 nights—ANOSIM Global R = 0.68, $P < 0.01$). Pairwise tests revealed that the 25 and 31 mm bunts were significantly different to the control (R = 0.918, $P < 0.01$ and R = 0.923, $P < 0.05$ respectively) but not to each to other (R = 0.167, $P > 0.05$) (Fig. 5). SIMPER analyses of these two groups (i.e. control vs. treatment trap nets) showed that all species of penaeids, along with several species of small fish (including glassy perchlets, whitebait, southern herring, gobies, hardyhead and river garfish) were responsible for the differences between the control and treatment trap nets (Table 3).

ANOVA of the appropriate univariate data from experiment 2 detected significant F ratios for the main effect of trap nets for the numbers of total, greasyback and eastern king prawns, hardyhead, river garfish and glassy perchlets (Table 4). SNK tests of these means showed that the 31 mm bunt retained significantly fewer total and eastern king prawns than the commercially-used 25 mm bunt (mean reductions of 44 and 52% respectively) and the control (Fig. 6A and C). Although not significant, the weights of total and eastern king prawns showed similar trends (Fig. 6B and D). Similarly, the 31 mm bunt caught fewer greasyback prawns and river garfish than did the 25 mm bunt (by 50 and 73% respectively) (Fig. 6G and J). Both treatment bunts retained comparable, and significantly fewer hardyhead and glassy perchlets than the control (Fig. 6I and K). Significant interactions were detected between nights and trap nets for the weight of greasyback prawns and the number of southern herring (Table 4). Like the results from above, the appropriate means of these differences revealed that the 31 mm bunt retained lower quantities of these species across most nights (Fig. 7A and B).

TABLE 4. – F ratios from analysis of variance to determine the effects on catches due to different trap nets and nights. All data were ln(x+1) transformed. $^{**}P < 0.01$; $^{*}P < 0.05$. Pld indicates that the interaction was non-significant at $P < 0.25$ and the sums of squares pooled with the residual.

		Total prawns		Greasyback prawns		King prawns		School prawns		Wt of
Source	df	no.	wt	no.	wt	no.	wt	no.	wt	bycatch
Trap net	2	9.45**	2.13	6.77**	2.27	4.87*	1.35	1.81	1.70	0.48
Nights	5	1.16	1.85	16.12**	29.19**	1.59	0.88	7.13**	5.87**	11.97**
Interaction	10	0.82^{pld}	0.77^{pld}	0.58^{pld}	3.67**	1.18^{pld}	0.90^{pld}	0.72^{pld}	0.41^{pld}	2.02
Residual	18									

Source	df	No. of southern herring	No. of hardyhead	No. of river garfish	No. of glassy perchlets	No. of broad squid
Trap net	2	0.98	8.30**	7.21**	98.70**	1.49
Nights	5	17.92**	1.27	1.52	0.58	48.16**
Interaction	10	3.25*	0.32^{pld}	0.44^{pld}	1.16^{pld}	1.53
Residual	18					

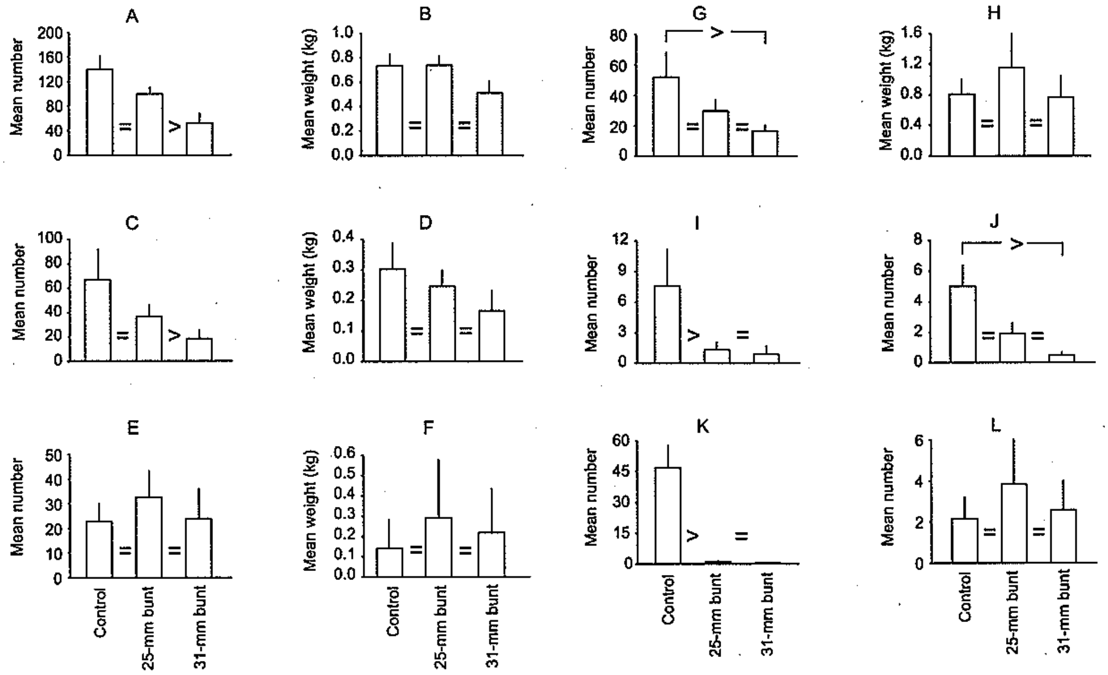

FIG. 6. – Differences in mean catch (+ SE) between the control and 25 and 31 mm bunts used in experiment 2 for A) number and B) weight of total prawns, C) number and D) weight of eastern king prawns, E) number and F) weight of school prawns, G) number of greasyback prawns, H) weight of bycatch and numbers of I) hardyhead, J) river garfish, K) glassy perchlets and L) broad squid. > and = indicate signif icant differences determined by SNK tests.

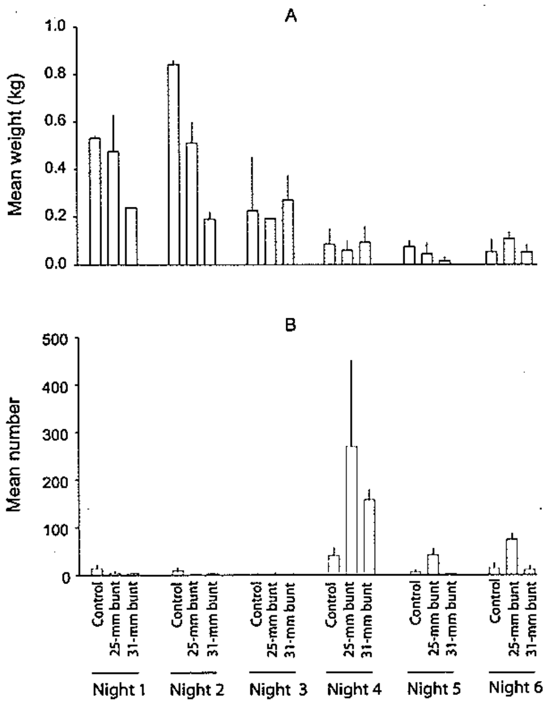

FIG. 7. – Differences in mean catch (+ SE) between the control and 25 and 31 mm bunts and nights in experiment 2 for A) weight of greasyback prawns and B) number of southern herring.

DISCUSSION

This study showed that (i) the commercially-used trap-net configurations had comparable and appropriate selectivity parameters for the targeted sizes of all three species of penaeids, and (ii) these trap nets are considerably more selective than other larger-meshed, static and towed gears used to target penaeids in south eastern Australia and throughout many other temperate and tropical fisheries (Vendeville, 1990; Sobrino *et al.*, 2000; Broadhurst *et al.*, 2004; Macbeth *et al.*, 2004). More specifically, the 25 mm bunt trap net selected all species at L_{50}s between 18.53 and 19.42 mm across SRs that were less than 3.4 mm (Table 2). This minimal inter-specific variability in selectivity parameters can be attributed to the considerable appendages and morphological discontinuities of penaeids, which strongly influence their selectivity irrespective of the species (Vendeville, 1990). These comparable L_{50}s and narrow SRs mean that the majority of all individuals of the 3 species less than between approximately 18 and 20 mm CL escaped through the 25 mm mesh. These escapees were larger than the average industry-accepted commercial sizes (approx 15-17 mm CL; Broadhurst *et al.*, 2004) targeted throughout all estuarine fisheries.

The selectivities of the commercially-used trap nets can be compared with other penaeid-fishing gears using a simple proportionality constant termed the 'selection factor' (SF) (Pope *et al.*, 1975) or 'coefficient of selectivity' (Vendeville, 1990), calculated by dividing the size of mesh into the L_{50} estimate. For the commercial trap nets examined here, all penaeid SFs ranged between 0.74 and 0.86. These values are considerably greater than those typically recorded for penaeid otter trawls, seines and stow nets, which frequently are less than 0.45 (e.g. Vendeville, 1990; Sobrino *et al.*, 2000) and often lower than 0.30 (e.g. Broadhurst *et al.*, 2004; Macbeth *et al.*, 2004). For example, in a study examining the selectivity of conventional otter trawls used in the Clarence River, NSW, Broadhurst *et al.* (2004) demonstrated that codends made from 40 mm diamond-shaped mesh had L_{50}s of 8.6 and 10.3 mm (i.e. SFs of 0.21 and 0.26) and SRs of 3.9 and 3.5 mm for school and eastern king prawns respectively. Although constructed from meshes that were almost 40 % smaller than these trawl codends, the commercially-used trap nets selected individuals at L_{50}s that were more than 2.5 times greater. Further, this selection occurred across a substantially narrower range of sizes.

Such a relatively more-defined selection by trap nets can be attributed to their design and method of operation. Hauling the headline and footrope of the entire posterior section (i.e. approx. 70 m) over the dory effectively spread large transverse sections of the netting (e.g. > 2 m) and maintained the maximum lateral mesh openings at an area where the catch was dispersed and being progressively rolled towards the bunt (Fig. 2C). This facilitated multiple contacts between all individuals in the catch and open meshes, providing numerous opportunities for selection to occur. In contrast, most of the selection processes in otter trawls, seines and stow nets occur in the codend. At this location, the mesh openings are mostly orientated parallel to the general movement of catch, frequently narrow in proportion to the mesh size, and often blocked by the distribution of the catch (Suuronen and Millar, 1992; Erickson *et al.*, 1996). These characteristics limit the probability of small organisms contacting open meshes and escaping.

The selection mechanisms described above for trap nets provide one explanation for the relatively high SRs observed for all penaeids from the 31 mm bunt (Fig. 4, Table 2). Owing to an increase in L_{50} proportional to the mesh size, this bunt maintained a SF of between 0.67 and 0.8 for all species. However, unlike the commercially-used 25 mm trap-net configurations, this selection occurred over a wide range of sizes (e.g. SRs ± SE between 4.36 ± 0.87 and 3.90 ± 1.55 mm, Table 2) more characteristic of towed gears. These wide SRs may be attributed to the comparatively short overall length (i.e. < 20 m) of larger-meshed netting available to select individuals in the 31 mm bunt section and their fewer contacts with open meshes as they were rolled towards the dory. Given the observations for the 25 mm trap nets, it is likely that the SRs of penaeids would be reduced if the entire posterior section (i.e. 70 m) was made from the 31 mm netting (and not just the 20 m bunt section).

Considering the results from the analyses of catch comparisons in experiment 2, it is apparent that using such a larger-meshed trap net would provide little benefit in terms of reducing unwanted bycatch while maintaining commercial catches. For example, MDS and the subsequent ANOSIM tests failed to detect any significant differences in overall catch structures between the 31 and the 25 mm bunts (Fig. 5). Compared to the control, both configurations were similarly effective in excluding large quantities of those small fish (such as whitebait, gobies, glassy perchlets and hardyhead) that typically inhabit coastal lakes and estuaries throughout NSW and are vulnerable to capture by penaeid-catching gears (e.g. Andrew *et al.*, 1995; Liggins and Kennelly, 1996; Liggins *et al.*, 1996; Gray, 2001) (Fig. 6, Tables 3 and 4). Further, there was no concomitant increase in the selection of southern herring (the most common larger-sized species), probably because this species has a high dorsal profile that limits their escape through diamond meshes, regardless of their size. The 31 mm bunt did exclude considerably greater numbers of small prawns, but a large proportion of commercial-sized individuals also escaped (Fig. 6A and C).

The results presented here confirm anecdotal claims by fishers that the trap-net configurations used in NSW selectively harvest penaeids across well-defined and targeted sizes. Compared to most other penaeid-catching gears, trap nets intuitively are less likely to negatively impact estuarine habitats. Future research into ways of mitigating the perceived deleterious effects of commercial penaeid fishing gears in some areas may therefore benefit from considering the utility and benefits of this fishing method.

ACKNOWLEDGEMENTS

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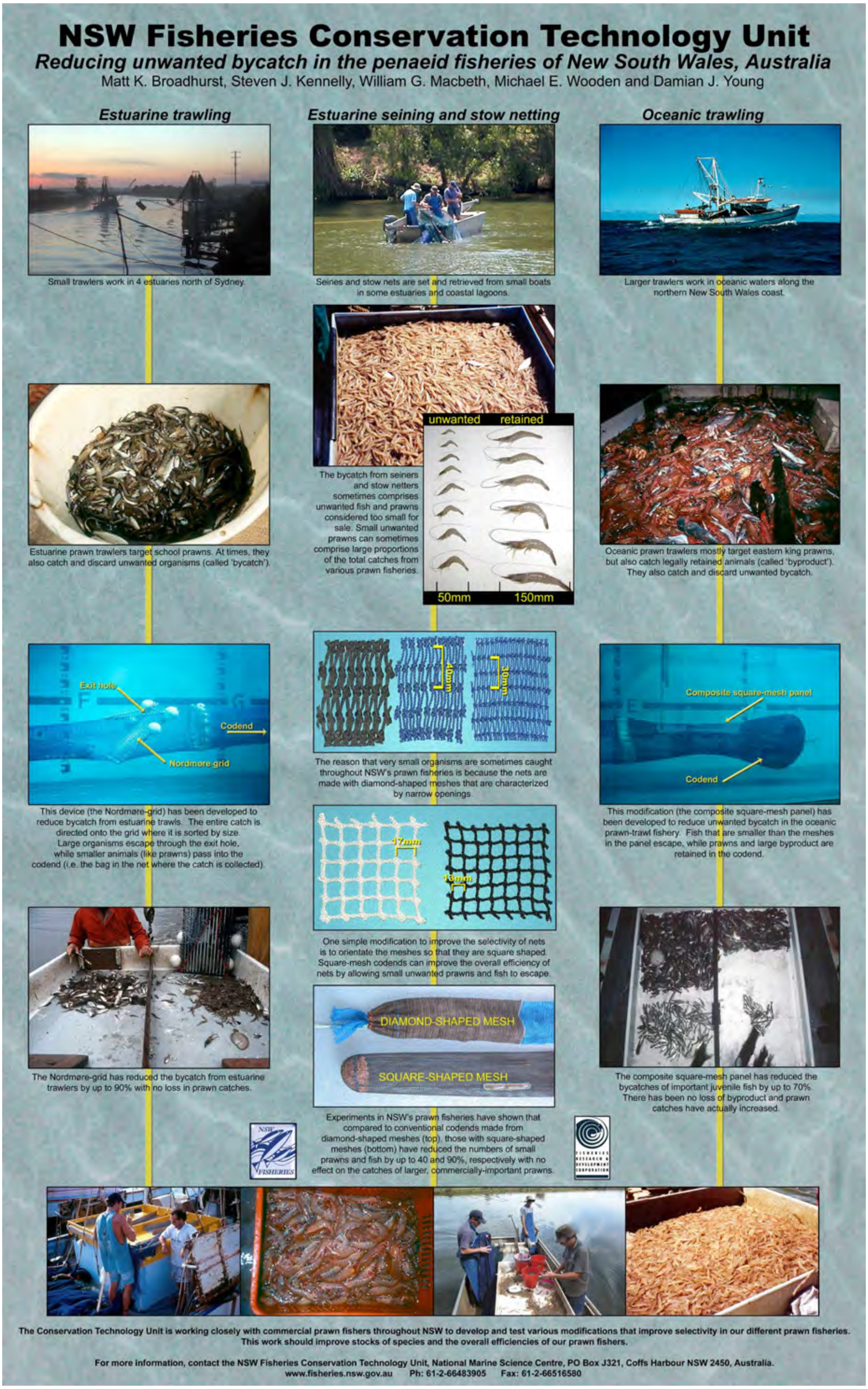
Appendix 13 - Broadhurst, M.K., Kennelly, S.J., Macbeth, W.G., Wooden, M.E. and Young, D.J. 2004. Reducing unwanted bycatch in the penaeid fisheries of New South Wales, Australia. Poster presentation at the 4th World Fisheries Congress.


NSW Fisheries Conservation Technology Unit
Reducing unwanted bycatch in the penaeid fisheries of New South Wales, Australia
Matt K. Broadhurst, Steven J. Kennelly, William G. Macbeth, Michael E. Wooden and Damian J. Young
Estuarine trawling
Estuarine seining and stow netting
Oceanic trawling
Small trawlers work in 4 estuaries north of Sydney.
Seines and stow nets are set and retrieved from small boats in some estuaries and coastal lagoons.
Larger trawlers work in oceanic waters along the northern New South Wales coast.
unwanted
retained
50mm
150mm
Estuarine prawn trawlers target school prawns. At times, they also catch and discard unwanted organisms (called 'bycatch').
The bycatch from seiners and stow netters sometimes comprises unwanted fish and prawns considered too small for sale. Small unwanted prawns can sometimes comprise large proportions of the total catches from various prawn fisheries.
Oceanic prawn trawlers mostly target eastern king prawns, but also catch legally retained animals (called 'byproduct'). They also catch and discard unwanted bycatch.
Exit hole
Codend
Nordmøre-grid
40mm
30mm
Composite square-mesh panel
Codend
This device (the Nordmøre-grid) has been developed to reduce bycatch from estuarine trawls. The entire catch is directed onto the grid where it is sorted by size. Large organisms escape through the exit hole, while smaller animals (like prawns) pass into the codend (i.e. the bag in the net where the catch is collected).
The reason that very small organisms are sometimes caught throughout NSW's prawn fisheries is because the nets are made with diamond-shaped meshes that are characterized by narrow openings.
This modification (the composite square-mesh panel) has been developed to reduce unwanted bycatch in the oceanic prawn-trawl fishery. Fish that are smaller than the meshes in the panel escape, while prawns and large byproduct are retained in the codend.
17mm
13mm
One simple modification to improve the selectivity of nets is to orientate the meshes so that they are square shaped. Square-mesh codends can improve the overall efficiency of nets by allowing small unwanted prawns and fish to escape.
DIAMOND-SHAPED MESH
SQUARE-SHAPED MESH
The Nordmøre-grid has reduced the bycatch from estuarine trawlers by up to 90% with no loss in prawn catches.
The composite square-mesh panel has reduced the bycatches of important juvenile fish by up to 70%. There has been no loss of byproduct and prawn catches have actually increased.
Experiments in NSW's prawn fisheries have shown that compared to conventional codends made from diamond-shaped meshes (top), those with square-shaped meshes (bottom) have reduced the numbers of small prawns and fish by up to 40 and 90%, respectively with no effect on the catches of larger, commercially-important prawns.
NSW FISHERIES
The Conservation Technology Unit is working closely with commercial prawn fishers throughout NSW to develop and test various modifications that improve selectivity in our different prawn fisheries. This work should improve stocks of species and the overall efficiencies of our prawn fishers.
For more information, contact the NSW Fisheries Conservation Technology Unit, National Marine Science Centre, PO Box J321, Coffs Harbour NSW 2450, Australia.
www.fisheries.nsw.gov.au Ph: 61-2-66483905 Fax: 61-2-66516580

Appendix 14 - Broadhurst, M.K. 2003. Reducing unwanted bycatch and improving selectivity in NSW prawn fisheries. Professional Fisherman, October 2003, p. 16-17.

Reducing unwanted bycatch and imp

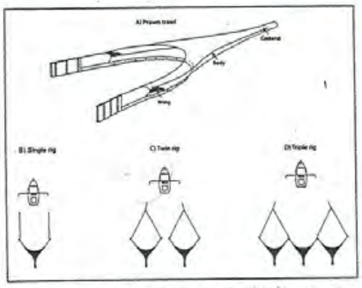


Fig.1. A) typical prawn trawl and B) single-, C) twin- and D) triple-rigged configurations

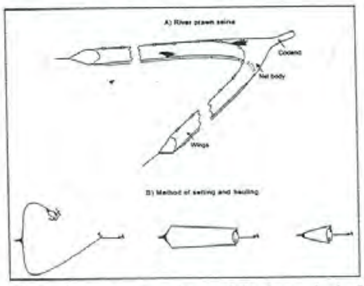


Fig.2. A) river prawn seine and B) the method of setting and retrieving the gear

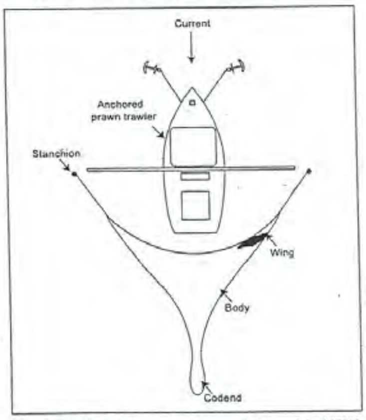


Fig.3. Typical stow net configuration used in NSW

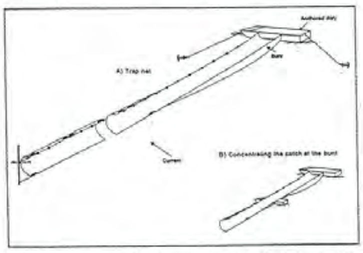


Fig.4. Diagrammatic representation of A) traps nets during fishing and B) using a dory to progressively concentrate the catch towards the bunt

Prawns form the basis of several important commercial fisheries throughout New South Wales with a total value of more than $26 million per annum.

Catches include six species, although eastern king (*Penaeus plebejus*), school (*Metapenaeus macleyi*) and greasyback prawns (*Metapenaeus bennettae*) account for more than 98 per cent of the total annual production (approximately 2,000 tonnes). These species are targeted throughout coastal and estuarine areas using four types of fishing gears that include: trawls (Fig. 1), seines (Fig. 2), stow nets (Fig. 3) and trap nets (Fig. 4).

Trawls are the most widely-used gear, with up to 246 vessels towing single and twin-rigged nets (Fig. 1B and C) to mostly target school prawns during the day throughout four estuaries and 312 vessels towing triple-rigged nets (Fig. 1D) to target king prawns at night offshore from Newcastle to the Queensland boarder. Seines are the second most common gear (Fig. 2) and are used by up to 191 fishers working in about 15 rivers and coastal lagoons.

Although the designs of seines vary slightly among these areas, the basic fishing method involves using anchors, buoys and ropes to set and haul a single net in a semi-circular configuration from small dories (Fig. 2B). Similar in principle to trawls, seines actively direct prawns along the wings and the body of the net and into the codend (Figs 1 and 2). In contrast to these towed gears, stow and trap nets are static and catch prawns by exploiting their migratory behaviour within estuaries. These gears are secured to the bottoms of rivers and coastal lagoons using anchors and stanchions and are usually fished at night between the last and first quarter phases of the moon. Stow nets are fished by up to 180 operators throughout six rivers. Prawns and other organisms move into the stationary stow net (which resembles a trawl or short seine) and are washed through to the codend by the flow generated during tidal movements and/or from an anchored vessel's propeller (Fig. 3). Trap nets are used throughout 12 coastal lakes by up to 95 operators. All of the trap nets are similar and comprise a wall of mesh secured between a vertical stanchion located near the shore and the horizontal gunwale of a dory anchored on a lake (Fig. 4A). Wind-generated currents cause the netting to assume a parabolic shape, effectively trapping migrating prawns and directing them along the wall

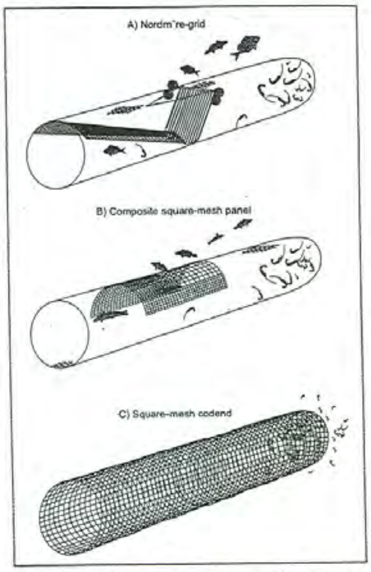


Fig.5. The A) Nordmøre-grid used in NSW estuarine prawn trawls, B) composite square-mesh panel used in oceanic prawn-trawl codends and C) entire square-mesh codends used in otter trawls, seines and stow nets

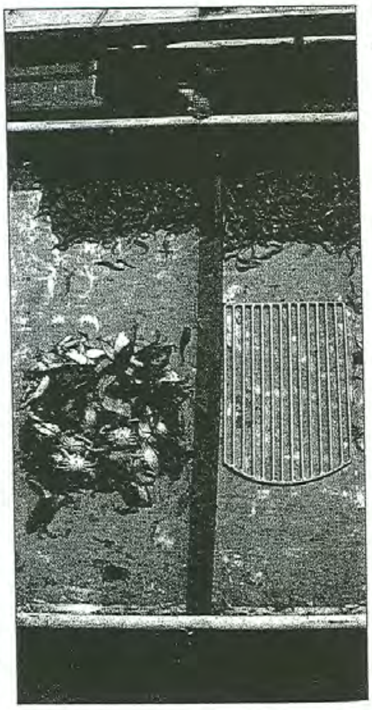


Fig.6. Simultaneous catches from otter trawl codends without (left) and with (right) the Nordmøre-grid

16 October 2003 **PROFESSIONAL FISHERMAN**

ng selectivity in NSW prawn fisheries

By MATT BROADHURST*

of netting towards the horizontally orientated bunt at the dory. Fishers facilitate this movement of catch by regularly lifting and hauling sections of the trap net over a dory so that it passes underneath the trap net and the catch is rolled towards the bunt (Fig. 4B).

All of the prawn-catching gears used in NSW are managed by limits on their methods and areas of operation, effort, dimensions and minimum and maximum legal-mesh openings. These legal-mesh openings vary between 40 and 45mm in the codends of trawls, 30 and 36mm throughout seines and stow nets and 25 and 36mm throughout trap nets. Over the past 20 years, the use of all of these small-meshed gears (and especially trawls) throughout areas known to have diverse and abundant fauna has raised concerns. Primarily, these concerns are directed towards the potential for large mortalities of juveniles of commercially and/or recreationally important fish, cephalopods and crustaceans and the possible negative impacts on their stocks. This has led to considerable efforts to reduce unwanted bycatch and improve the selectivity of the various gears.

Owing to their wide-scale use throughout estuarine and oceanic areas, and often large bycatches, trawls have received the majority of attention. The most common method for improving the selectivity of these gears involves installing physical modifications termed "bycatch reduction devices" or "BRDs" in the codends (where the catch is retained and most of the selection processes occur) (Fig. 5A and B). BRDs are designed to allow unwanted organisms to escape, while maintaining catches of the targeted species. For many estuarine prawn trawls, a BRD comprising a rigid aluminium grid located at an angle in the trawl (termed the "Nordmøre-grid" – Fig.5A) was shown to be effective in reducing up to 90 per cent of unwanted bycatch with no effect on the catches of prawns (Fig. 6). In oceanic areas, trawlers are allowed to retain and sell some of their fish, cephalopods and crustaceans that regularly comprise bycatch (termed "byproduct") and so the Nordmøre-grid (which excludes almost everything, except prawns) was considered unsuitable for use in this fishery. Instead, a BRD (termed the "composite square-mesh panel") that only excludes small fish was developed (Fig. 5B). This BRD is effective in allowing up to 70 per cent of the juveniles of commercially important fish

Fig.7. Sizes of small prawns discarded from NSW's prawn fisheries

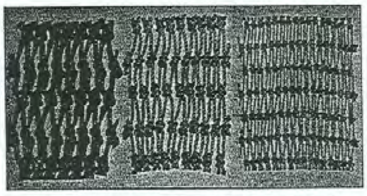


Fig.8. Diamond-shaped meshes used in the codends of otter trawls (left and middle) and seine and stow nets (right)

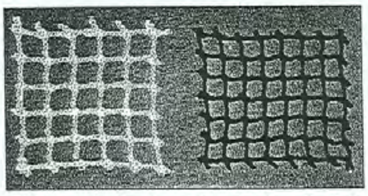


Fig.9. Square-shaped meshes used in codends to improve size selectivity

like whiting (*Sillago spp.*) and flatheads (*Platycephalus spp.*) to escape, with no effect on the catches of prawns or important byproduct.

The BRDs developed for prawn trawls have alleviated many of the problems associated with the issue of bycatch in NSW. These sorts of modifications generally have not been required in seines, stow nets and trap nets because they retain comparably fewer juveniles of important fish and cephalopods. The main bycatch concern for these fishing gears is juvenile prawns considered too small for sale (Fig. 7). Small, unwanted prawns can constitute a significant problem for most gears at many locations and especially seines, stow nets and trawls used in estuaries. The retention of small prawns by these gears is due to the rigging arrangements of their conventional codends and the small diamond-shaped meshes, which have very narrow lateral openings (Fig. 8). Trap nets also have similar-sized, diamond-shaped meshes throughout, but their method of operation ensures that these meshes remain wide open during fishing and this allows small organisms ample opportunities to escape.

The simplest way to improve the selectivity of trawls, seines and stow nets is to ensure that they also maintain sufficient openings during fishing. This can be achieved by orientating meshes in the codend so that they are square shaped (Fig. 9). More specifically, research has shown that codends made entirely from square mesh (Fig. 5C) between approx. 60 and 80 per cent of the size of the conventional diamond-shaped meshes are quite effective in significantly reducing the numbers of small unwanted prawns and other organisms, with no effect on the catches of target species. Where required, these square-mesh codends can be combined with BRDs (e.g. in trawls) to considerably improve the overall selectivity of the fishing gear.

The modifications developed to improve the selectivity of NSW's prawn-fishing gears should greatly reduce the mortality of many of the species comprising bycatches and the potential for negative impacts on their stocks. Research examining the fate of small individuals of species such as bream (*Acanthopagrus australis*), mulloway (*Argyrosomus japonicus*), sand whiting (*Sillago ciliata*) and school prawns after escaping from relevant BRDs and different mesh configurations provides strong support for positive benefits, with all species sustaining minimal physical damage and few long-term mortalities (between 0 and 11 per cent).

The NSW Fisheries Conservation Technology Unit is continuing to research ways of modifying prawn-fishing gears so they are more selective for the targeted species and their optimal sizes. As with all other previous gear-related research, this is being done in close consultation and collaboration with relevant industries and on a fishery-specific basis. This will ensure the ongoing refinement, adoption and eventual legislation of recommended changes.

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