Development of by-catch reducing prawn-trawls and fishing practices in NSW's prawn-trawl fisheries

(and incorporating an assessment of the effect of increasing mesh size in fish trawl gear)

Steven J. Kennelly & Matt K. Broadhurst

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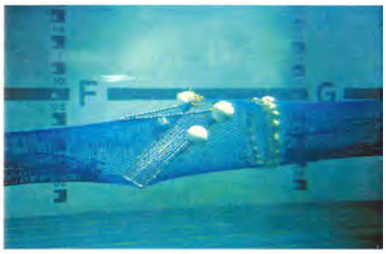

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Table of Contents

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

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OBJECTIVES:

1. To develop and test (using a series of controlled, replicated, manipulative field experiments throughout NSW's estuarine and oceanic prawn-trawl fisheries) a variety of modified prawn trawl gears and fishing practices which maintain catches of prawns at those levels caught by conventional methods but exclude the unwanted by-catch of juvenile fish;
2. To determine the most appropriate design(s) of these gears and practices for each of NSW's estuarine and oceanic prawn-trawl fisheries, recommend their implemention and assist fisheries managers in this implementation.

In response to a request from FRDC, we were given extra funding to address an additional objective:

3. To investigate the impact on catch and by-catch due to increasing mesh-size in fish trawls from 90mm to 100mm.

KEYWORDS: By-catch reduction, prawn-trawl, fishing gear

NON-TECHNICAL SUMMARY:

This summary briefly describes the work done throughout this 3 year project, the details of which can be found in a total of 19 scientific papers (see Appendix 4), 5 papers given at international conferences, 16 non-journal publications, 1 PhD thesis and 2 video documentaries. In addition to this short summary, however, we direct readers to our latest video documentary entitled "By-catch reduction devices for NSW prawn-trawl fisheries". This 10 minute video provides an excellent non-technical summary of the project and includes underwater footage and other images that could not be included here.

The incidental capture of non-target species, collectively termed 'by-catch' from prawn-trawling has attracted world wide attention for many years. In NSW, these concerns arose from the perception that prawn-trawls catch and discard large numbers of juveniles of species that, when larger, are targeted in other commercial and recreational fisheries. A recent three-year observer study (FRDC project no. 88/108 - see Kennelly, 1993) quantified large by-catches of juveniles of commercially

and recreationally important species throughout NSW's estuarine and oceanic prawn-trawl fisheries. The current project was the obvious next step in ameliorating the problematic by-catches identified, by aiming to develop, test and implement fishing gears and techniques that reduce such by-catches.

To address these issues, we undertook a protocol of research with industry that: (i) developed appropriate By-catch Reducing Devices (BRDs) for most of the estuarine and oceanic prawn-trawl fisheries in NSW; (ii) executed manipulative experiments that assessed their performance; and (iii) got the majority of prawn trawlers in NSW using the new BRDs on a voluntary basis (a virtually unique case of industry-acceptance of BRDs). For the estuarine prawn-trawl fisheries of NSW, separator-panels that mechanically partitioned the catch (like the Nordmøre-grid) were found to be most suitable. Compared to commercial trawls, the Nordmøre-grid was effective in reducing the mean weight of by-catch by up to 90% and the numbers of commercially and recreationally important species (such as bream) by up to 67% with no significant reductions in catches of prawns. In the oceanic prawn-trawl fishery, panels of square-shaped mesh located in the tops of the anterior sections of codends were effective in reducing by-catch that included non-target individuals and juveniles of commercially and recreationally important species (like whiting). Compared to standard commercial trawls, a trawl with a codend incorporating composite panels of square mesh was effective in reducing up to 41% of the total unwanted by-catch and up to 70% of the numbers of small red spot whiting. This new design had no significant effect on the catches of commercially important by-product (species that fishers are legally permitted to retain) and significantly **increased** catches of prawns (by up to 14%).

Getting industry to adopt new BRDs into their normal fishing operations was achieved by having them intrinsically and actively involved in all aspects of this project. In addition to the earlier observer programme, fishers were involved in this project during the early gear development stages, formal testing of gears, initial implementation onto vessels, voluntary adoption by fleets and, most recently, the public liaison and legislative stages. Such involvement of fishers throughout all this work has meant that the new BRDs are being used by the majority of fishers voluntarily (a virtually unique situation for the implementation of BRDs throughout the world).

In addition to this involvement of industry, we executed an extensive liaison programme with the prawn-trawl industry, other commercial and recreational fishers, the press and public through the production of colour posters, T-shirts and video documentaries that were distributed to prawn trawlers, commercial and recreational fishers, various committees, fish-and-chip shops, seafood outlets, fishermen's co-operatives, the television, radio and print media, schools, universities and the general public. We also made many presentations about the work to port meetings, fishing clubs, the press, PRO-AM meetings, schools, universities, national and international conferences, etc.

During this project we assessed species-specific physiological responses to stimuli from trawls to determine the mechanisms by which fish escaped from BRDs. In the oceanic prawn-trawl fishery, we showed that operational procedures, corresponding changes in the geometry of the codend, differences in the circumference of codends and changes in water flow significantly influenced the behaviour of some species and their ability to escape through square-mesh panels. For example, a delay in haulback of 15 seconds was effective in allowing large numbers of red spot whiting to escape but had no effect on the behaviour of other species. Similarly, increased codend circumference and an associated displacement of water forwards facilitated greater escape of some species through square-mesh panels but had no effect on species such as stout whiting.

An additional piece of work assessed the survival of fish escaping though our BRDs. To examine this important issue, we executed a series of laboratory experiments to assess the damage and mortality incurred by juvenile yellowfin bream, mulloway and whiting after simulated escape through the guiding panel of a Nordmore-grid and square-mesh panels. The results showed little damage to fatigued and non-fatigued fish after passing through these devices (less than 4% scale-loss) and negligible mortalities compared to control fish.

Soon after starting this project, FRDC requested us to accept additional funding to incorporate a study on the effects of increasing mesh-size in fish trawls. In this experiment, we compared the catches of finfish from a conventional fish trawl (constructed of 90 mm mesh in the body and codend) with those from a fish trawl constructed of 100 mm mesh. Catches from the 100 mm trawl showed a mean reduction of 27% in all by-catch and a 28% mean reduction in the numbers of retained tiger flathead compared to the conventional trawl. The 100 mm trawl also showed 48% and 47% mean reductions in the numbers and weights of discarded tiger flathead respectively and 57% and 63% mean reductions in the numbers and weights of discarded rubberlip morwong respectively. For john dory, however, at a particular location where large numbers occurred, the 100 mm trawl caught significantly more fish than did the conventional trawl (a mean increase in weight of 66%). We concluded from this work that there is an urgent need to determine species-specific mesh selectivities for fish trawling.

This project was successful in developing new gears to reduce by-catch in NSW's prawn trawl fisheries, achieving their widespread voluntary adoption (which should soon become mandatory), decreasing the conflict over by-catch in these fisheries and conserving estimates of millions of juvenile fish of many different species. This success leads us to conclude that the best course of action for future research and development on by-catch reduction in NSW's prawn-trawl fisheries should remain in the hands of the fishers themselves, with little urgent need for additional formal research (at least for the time-being). Funds would be better spent on by-catch issues involving other methods and on the selectivity of target species.

Background

In Australia, concern about the deleterious impacts of by-catch from prawn fishing began as early as the late nineteenth century when a Royal Commission examined the fisheries of NSW (Macleay et al., 1880). Conflict between amateur and professional fishermen over the reputed by-catch of the "sunken prawn net" led to the NSW Department of Fisheries doing the first recorded survey of by-catch in Australia (Dannevig, 1904). Little had changed in Australia during the next 90 years or so, with the by-catch from prawn trawling still of great concern to a broad cross-section of the community, particularly commercial fishers other than trawlers (e.g. fish trappers, set and hand-liners, mesh netters, beach seiners), recreational fishers, conservationists, environmentalists, fisheries managers, scientists and politicians from all levels of government. Of major concern have been complaints regarding prawn trawlers catching and discarding large numbers of undersize fish that, when larger, are targeted in other commercial and recreational fisheries. In particular, these observations are made with respect to prawn trawling in estuarine and oceanic locations thought to be nursery grounds for important species of fish. Worldwide concern over this issue has increased markedly in recent years (for reviews see Andrew & Pepperell, 1992; Alverson et al., 1994; Kennelly, 1995) and in Australia, this resulted in our recently completed project on prawn-trawl by-catch quantification (Kennelly, 1993) and the current spate of research projects funded by FRDC examining ways to reduce prawn-trawl by-catch.

The recently-completed prawn-trawl by-catch project (FIRDC project No. 88/108 - Kennelly, 1993) successfully identified and quantified the catches and by-catches from a large proportion of NSW's oceanic and estuarine prawn-trawl fisheries. In so doing, the results identified the key species, regions and times involved in interactions with other commercial and recreational fisheries (e.g. see Liggins & Kennelly, 1996; Liggins et al., 1996; Kennelly et al., in press). Because of this work, we were in an excellent position to consider ways that may solve the substantial conflicts that occur between different user groups over the by-catch and discarding of large numbers of juvenile finfish such as snapper, mulloway, whiting, flathead and bream.

Need

The most obvious research and management strategy that arises whenever people discuss prawn trawl by-catch of unwanted juvenile fish concerns an examination of gear selectivity and fishing practices. Modifications to prawn-trawl nets, codends, sweeps and fishing practices are all alternatives that have been, and will continue to be, invoked throughout the world as means for solving by-catch problems. Work done in other countries and in NSW indicate that it is possible to develop modifications to trawl gear and fishing practices that will negate a great deal of the capture and mortality of by-caught finfish. Work done previously by NSW Fisheries showed the very real potential of soft TEDs (Trash Elimination Devices) and varying sweep lengths as means for reducing the incidental capture of finfish (Andrew et al., 1991; 1993). Unfortunately, however, at the time of beginning this new project, these few papers represented two of only four published studies concerning by-catch reduction technology in Australia (see also Sumpton et al., 1989; Mounsey & Ramm, 1991). As noted in a recent review (Kennelly, 1995), most work in this field in Australia had concentrated on describing the problems of trawl by-catch via quantifications of the species and abundances taken in various prawn fisheries through surveys using onboard observers and research vessels. In Australia, we have been quite slow (Dannevig's study was done 94 years ago!) to move onto the next step in addressing this issue which is to examine various management strategies which may reduce by-catch.

This present project examines fully the utility and effectiveness of various gear modifications and fishing practices as means to reduce problematic and undesirable by-catches in NSW's estuarine and oceanic prawn-trawl fisheries.

Objectives

The specific objectives of this study were:

1. To develop and test (using a series of controlled, replicated, manipulative field experiments throughout NSW's estuarine and oceanic prawn-trawl fisheries) a variety of modified prawn trawl gears and fishing practices which maintain catches of prawns at those levels caught by conventional methods but exclude the unwanted by-catch of juvenile fish;

2. To determine the most appropriate design(s) of these gears and practices for each of NSW's estuarine and oceanic prawn-trawl fisheries, recommend their implemention and assist fisheries managers in this implementation.

In response to a request from FRDC, we were given extra funding to address an additional objective:

3. To investigate the impact on catch and by-catch due to increasing mesh-size in fish trawls from 90mm to 100mm.

Methods

A wide variety of experiments were done during this project at sea, in estuaries and laboratories. A summary of the locations and methods used are contained in Table 1 (see below) and details can be found in the papers provided in Appendix 4 of this report.

We developed and tested various By-catch Reduction Devices (BRDs) in the estuarine prawn-trawl fisheries in the Clarence River, Lake Woolooweyah, Hunter River, Hawkesbury River and Botany Bay and in the oceanic fisheries operating out of the ports of Ballina, Iluka, Yamba, Coffs Harbour, South West Rocks, Port Stephens and Newcastle. This includes most of the places where prawn trawling occurs in NSW.

In general, our experiments took the form of paired comparisons of gears - usually one trawl was a conventional net used as a control and the other was some type of modified trawl containing a BRD. In estuaries we usually chartered twin-rigged prawn trawlers to facilitate these paired comparisons (although we also used trouser trawls, alternate hauls, and the two outer nets on triple gear in single-gear estuarine fisheries). Offshore we did our paired comparisons using the two outer nets on chartered vessels operating with triple-rigged configurations.

Using chartered commercial vessels to do this research (rather than research vessels) proved vital because: (i) it utilised skippers and crews who possessed local knowledge of the conventional methods used and local fishing grounds; (ii) it supplied control gears (e.g. conventional nets) against which the modifications were tested; and (iii) it ensured the interest and involvement of the whole fleet (i.e. including those not chartered for the research) because the research was done with their colleagues, alongside them, on their grounds, using similar gears and vessels. It is important to note that the first modifications trialed in these experiments were simple changes (e.g. holes in the upper codend) which introduced the ideas of by-catch reduction gradually to fishers. Testing of the more complicated grids and panels çame later - once fishers were familiar with the basic concepts.

During our paired comparisons, we swapped different codends (i.e. the control and that containing the BRD) at random to account for any unknown biases between nets and sides of the vessel. For each trial, we completed many replicate tows in a variety of conditions to provide adequate power for statistical analysis. We recorded information on the weights of prawns, all retained and discarded by-catch species and the size-structures of prawns and by-catch species. That is, we recorded almost all the information that could be obtained from each codend trialled. We rarely subsampled catches, preferring to get as complete a set of data from each codend as possible. In general, we analysed our data using paired t-tests, multifactorial analyses of variance, Student-Newman-Keuls multiple comparisons and Kolmogorov-Smirnov tests.

We also recorded all aspects of our work on film (as colour slides, prints and VHS video). We also invested a substantial sum on gaining excellent underwater footage of our BRDs working *in situ*. We did additional experiments in the Australian Maritime College's flume tank to examine flow rates in our BRDs and we completed a series of experiments to assess any damage and mortality incurred by fish escaping our BRDs using the aquarium facilities at NSW Fisheries Research Institute.

The adoption of BRDs by industry was achieved through a continuous programme that had industry intrinsically and actively involved in all aspects of the project. Starting with the earlier observer programme, fishers were next involved in the early gear development work, the formal testing of BRDs, their implementation onto individual vessels, voluntary adoption by whole fleets and, most recently, the public liaison and legislative stages. This history has meant that the new BRDs are being used by the majority of fishers on a voluntary basis (a virtually unique situation in the acceptance of BRDs).

Table 1 - Summary of the experiments done during this project. NB. ↑ denotes an increase, ↓ denotes a decrease, ns denotes no effect.

LOCATION	METHOD	TREATMENTS	RESULTS
ESTUARINE PRAWN TRAWL:			
Hawkesbury River	Alternate haul	Control vs. Full sq. mesh codend, Half sq. mesh codend	 ↓ 52% prawns, ↓ 95% juv. mulloway ns prawns, ↓ 46% juv. mulloway
Hawkesbury River	Trouser trawl	Control vs. a small sq. mesh panel	ns prawns, ↓ 49% juv. mulloway
Clarence River	Paired tows (twin gear)	Control vs. various separator mesh panels, Nordmore Grid	 ns prawns, ↓ 70% total by-catch ns prawns, ↓ 77% total by-catch
Clarence River	Paired tows (twin gear)	Control vs. blubber chute, Standard Nordmore Grid, Nordmore Grid minus guiding funnel (in flood)	ns prawns, ↓ 75% total by-catch ns prawns, ↓ 90% total by-catch ns prawns, ↓ 82% total by-catch (Standard Nordmore Grid caught more prawns than blubber chute)
Botany Bay	Alternate haul	Control vs. 100mm and 150mm separator panels	↓ 34% king prawns, ↓ 58% total by-catch
Hunter River	Paired tows (outside nets on triple gear)	Control vs. Nordmore Grid Blubber chute, fisheye extended mesh funnel, Allerio Bros. grid, sq. mesh panel	Nordmore Grid with all secondary designs had ↓ 45-58% total by-catch and ↑ 23-41% prawns vs. blubber chute. No advantage in using any secondary designs with the Nordmore Grid
OCEANIC PRAWN TRAWL:			
Yamba	Paired tows (outside nets on triple gear) and alternate haulback periods	Control vs. long sq. mesh panel, short sq. mesh panel, no delay in haulback, 10-15 sec delay in haulback	 ns prawns, ns by-product, ↓ 40% total by-catch ns prawns, ns by-product, ↓ 38% total by-catch Red spot whiting escaped during haulback delay
Iluka	Paired tows (outside nets on triple gear)	Codends with 100 mesh and 200 mesh circumference, composite sq. mesh panel	100 mesh - ns prawns, ns by-product, ↓ 40% total by-catch vs. 200 mesh. Composite sq. mesh panel led to ns prawns, ns by-product, ↓ 40% total by-catch between 100 and 200 mesh.
Pt Stephens S W Rocks Yamba Ballina	Paired tows (outside nets on triple gear)	Control vs. composite sq. mesh panel throughout NSW	↑ 5-14% prawns, ↓ 23-41% total by-catch
OCEANIC FISH TRAWL:			
Newcastle Bermagui	Alternate haul	Control (90mm net) vs. 100mm net	↓ 27% total by-catch, ↓ 28% ret'd tiger f'hd, ↓ 47% disc'd tiger f'hd, ↓ 47% disc'd rubberlip morwong, ↑ 66% john dory

Table 1 - Continued

LABORATORY EXPERIMENTS:

FRI	Treatments replicated across many small tanks	Scale-loss and survival of fatigued and non-fatigued whiting passing through sq. mesh panels	↑ 67-84% scale-loss for fatigued fish compared to non-fatigued. Maximum scale loss only 4% due to sq. mesh panel and negligible mortalities
FRI	Treatments replicated across many small tanks	Scale-loss and survival of bream passing through Nordmore Grid funnel and capture by hook and line	↑ 60-80% scale-loss after passing through funnel. ↑ 79-87% scale-loss after capture by hook and line. Maximum scale loss <3% and negligible mortalities. ↑ infection by parasites and mortality after capture by hook and line.
AMC	Treatments replicated across many runs in flume tank	Water flow measurements in 100 mesh vs. 200 mesh codends, with and without comp. sq. mesh panel, with different weights of catch	↑ water displacement forwards with 200 mesh section, varying with wt. of catch. Comp. sq. mesh panel increased anterior displacement of water.

Our industry and public liaison phase also involved: (i) the production of a colour poster describing our work which was distributed to prawn trawlers, most of the fish-and-chip shops, seafood stores and fishermen's co-operatives throughout NSW and given to the press, schools and general public; (ii) the production of two video documentaries which have been distributed to prawn trawlers, other commercial and recreational fishers, fishermen's co-operatives, the television and print media, schools, etc.; (iii) many presentations to fishing clubs, the press, port meetings, PRO-AM meetings, schools, universities, national and international conferences, etc.; and (iv) the production of T-shirts describing the project which were given to prawn trawlers and other interested individuals.

Results/Discussion

A summary of the results from the various experiments done during this project are given in Table 1. Detailed results and discussion of all our work are contained in the papers provided in Appendix 4.

In general, we found that the new gears developed (particularly the Nordmore Grid and composite square-mesh panel) reduced unwanted by-catches by large amounts in all fisheries examined. In doing this, these new developments did not lose any of the targeted prawns nor other desirable by-catch species (e.g. balmain bugs, octopus, squid, larger fish, etc.). In some cases, especially for the composite square-mesh panel, significant **increases** in prawn catches were recorded - probably due to better trawl performance due to decreasing the weight of unwanted by-catch in the codend.

Our work on the damage and mortality incurred by fish escaping from these devices showed negligible damage and mortality, even when fish were fatigued to exhaustion. This result indicates that virtually all the fish escaping our BRDs probably survived in good condition and should therefore be able to contribute to subsequent stocks.

The acceptance and adoption of our BRDs by industry is recognised as among the most successful in the world, with the majority of prawn trawlers in NSW using these gears on a voluntary basis. This result is now proving to be vital in the final (and relatively painless) stage of making these BRDs mandatory through the appropriate Management Advisory Committees.

Benefits

The most obvious and immediate benefit to come from this project has been a reduction in the conflict over by-catch from prawn trawling in NSW. This project has been successful in reducing the perception that large by-catches from prawn trawling causes widespread impacts on other fisheries.

Apart from this perceived problem, the benefits from this project in terms of actual impacts on subsequent stocks of fish should be large, widespread and involve most other marine fisheries in NSW. However, such cause-and-effect impacts are extremely difficult to quantify. Whilst it is often considered sufficient to develop and implement BRDs in fisheries, estimating their actual impact on subsequent stocks of escaping species need to incorporate estimates of several additional factors. Firstly, any mortality of fish after escape from BRDs must be determined and, in this project, we completed laboratory-based studies that found negligible damage and mortality of escapees. Secondly, one needs information on key population parameters of the escaping species, including their natural mortalities and growth rates, to determine the likelihood of their surviving to exploitable sizes after escape. Finally, it is necessary to have some understanding of the proportion of total biomasses that the escapees represent. For example, estimates of the escape of fish from BRDs that are in the order of millions of individuals, may be negligible if the total abundances of these fish are orders of magnitude larger.

Despite lacking the latter information, we nevertheless attempted to provide some estimates of possible consequences of our BRDs for two examples. To assess possible impacts of large reductions in by-catches of red spot whiting in the oceanic prawn-trawl fishery, we combined estimates of the potential reduction in by-catches (using BRDs), growth, natural mortalities and survival of escapees. These calculations showed that the widespread application of the composite square-mesh panel in this fishery may provide between 1.5 million to 3.3 million additional red spot whiting per year to other fisheries. For bream in an estuarine fishery, using similar assumptions and similar, poor estimates of population parameters, we estimated that if all vessels in the Clarence River had been fitted with Nordmøre-grids in the 1991-92 season, an additional 124,000 bream may have been available for capture in other fisheries.

In the absence of reliable estimates of natural mortality and other parameters, such figures will be questionable, but these calculations nevertheless illustrate that the current widespread use of BRDs developed in this project should increase the availability of many marine species to other commercial and recreational fisheries.

Further Development

A great deal of the work necessary to address the issue of by-catch reduction in NSW's prawn-trawl fisheries has been completed, published and disseminated during this project. After this success in ameliorating our most problematic by-catch issue (due to prawn trawling), we are now turning our attention to other by-catch issues in other fisheries (particularly estuarine hauling). However, our involvement of prawn-trawl fishers in this project and their desire to incorporate and improve BRDs means that, while we are ceasing active research in this field, we are leaving further development in the hands of those best positioned to do it - the prawn-trawl fishers themselves. Because the majority of prawn trawlers in NSW are now using BRDs voluntarily, many are continuing to try new modifications and re-tune old ones to reduce by-catches even further. In drafting our regulatory changes to ensure 100% adoption of BRDs into the future (currently being done through the appropriate Management Advisory Committees), we are being very careful to ensure that the regulations provide sufficient flexibility to encourage further development of BRDs by fishers.

For the above reasons, we feel that the best course of action for future research and development in by-catch reduction in the prawn-trawl fisheries of NSW should remain in the hands of the fishers themselves, with no urgent need for further formal research (at least for the time-being). Funds would be better spent on by-catch issues involving other methods and on the selectivity of target species.

Conclusion

This project has been recognised as one of the most successful completed in the field of by-catch reduction and industry acceptance of BRDs. The work involved testing existing gears, developing new ones, trialing them, re-tuning them and finalising designs that reduced problematic by-catches by large amounts with no reduction in catches of prawns or desired by-catch. Additional work quantified negligible damage and mortality of fish escaping from the new BRDs and examined the mechanisms of escape in terms of flow rates inside nets and the physiological responses of escaping fish. The industry acceptance and public liaison phases of the work were also successful, leading to an almost unique situation of widespread voluntary adoption of the new gears, a major decrease in conflict over by-catch in these fisheries and the estimated conservation of millions of juvenile fish of many different species. The success of this project has meant that - at least for the time-being - no additional formal research is required on this issue in NSW and that future research and development can rest in the hands of the prawn-trawl fishers themselves.

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Appendix 1 - Intellectual Property

All intellectual property and valuable information arising from this project is published in the scientific papers provided in Appendix 4. All these pieces of information, including the new BRDs developed, are free for use by anyone who wishes to use them. There are also no copyright restrictions on our latest 10 minute video documentary summarizing the project. We encourage the copying, dissemination and use of all the papers, videos and products that arose from this project (with appropriate acknowledgement and citation of the authors and publishers).

Appendix 2 - Staff

Dr Steve Kennelly (Principal Research Scientist) - Principal Investigator
Dr Matt Broadhurst (Senior Technical Officer)
Mr Gerard O'Doherty (Technical Assistant)

Appendix 3 - Publication list from this project (copies in Appendix 4)

Publications in scientific journals:

Broadhurst, M.K. and S.J. Kennelly, 1994. Reducing the by-catch of juvenile fish (mulloway *Argyrosomus hololepidotus*) using square-mesh panels in codends in the Hawkesbury River prawn-trawl fishery. Fisheries Research, Vol. 19, pp. 321-331.

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Appendix 4

Copies of papers from this project

Reducing the by-catch of juvenile fish (mulloway *Argyrosomus hololepidotus*) using square-mesh panels in codends in the Hawkesbury River prawn-trawl fishery.

Broadhurst, M.K. and S.J. Kennelly, 1994.

Fisheries Research, Vol. 19, pp. 321-331.

Fisheries Research, 19 (1994) 321–331

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Reducing the by-catch of juvenile fish (mulloway *Argyrosomus hololepidotus*) using square-mesh panels in codends in the Hawkesbury River prawn-trawl fishery, Australia

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Abstract

The numbers of prawns and small fish (mulloway) caught by two designs of prawn-trawl codends with square-mesh panels were compared in a manipulative field experiment in the Hawkesbury River prawn-trawl fishery. Compared with a conventional codend, catches from a codend made entirely of square meshes showed a 52% reduction in the mean weight of prawns caught and a 95% reduction in the numbers of mulloway caught. A codend with the posterior half made of diamond-shaped meshes and the anterior half made of square-shaped meshes showed no significant difference in the catches of prawns compared with the control, but reduced to 46% the mean numbers of mulloway caught. There were no differences in the sizes of prawns and mulloway caught by the half-square and the control codends. The codend made of all square meshes did not catch the smallest prawns and mulloway available. The results are discussed in terms of the probable behaviour of prawns and mulloway in trawls and the possibilities for future developments of these fishing gears. It was concluded that there is great potential for square-mesh panels in codends to reduce the by-catch of fish such as juvenile mulloway in the Hawkesbury River prawn-trawl fishery while maintaining catches of prawns.

Introduction

Estuarine prawn trawling occurs in five estuaries in New South Wales (N.S.W.), Australia, and is valued at approximately A$7 million per annum (1990–1991). As with most trawl fisheries, significant numbers of non-target organisms are caught incidentally with the targeted species (collectively termed 'by-catch', sensu Saila, 1983). In N.S.W., the by-catch from estuarine prawn trawling often includes a large and diverse assemblage of small fishes, some of which are juveniles of species caught in other commercial and recreational fisheries (Kennelly et al., 1992). The mortality of large numbers of

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these juveniles due to prawn trawling and the negative effects this may have on subsequent stocks of these species have resulted in significant conflicts between prawn-trawl fishers and other user groups (particularly recreational fishers) (see also Gordon, 1988; Foldren, 1989).

Mulloway (*Argyrosomus hololepidotus*) is an important commercial species in N.S.W. and a key target species for a large recreational fishery (Grant, 1985). It is a euryhaline demersal species inhabiting nearshore environments and estuaries during the juvenile stages of development (0–2 years) (Bennett, 1985). In N.S.W., this is evident from March to July each year when newly spawned individuals occur in several estuaries throughout the state.

The Hawkesbury River is an estuary in N.S.W. which supports a year-round school prawn (*Metapenaeus macleayi*) fishery valued at approximately A$725 000 per annum. A survey of the by-catches of prawn trawl fisheries throughout N.S.W. showed that there are relatively large by-catches of juvenile mulloway during winter months in the Hawkesbury River (Kennelly et al., 1992). The current management of this fishery is mainly based on spatial and temporal closures to trawling but, because of increasing conflicts with other fishers concerning the by-catch of juvenile finfishes, alternative procedures may be required if prawn trawling is to continue at those places and times where conflicts occur.

Recent studies on modifications to trawling gear have concentrated on designs that reduce by-catch while maintaining catches of prawns. Many of these studies have shown clear results and have often led to changes in the management strategies of the fisheries concerned (e.g. Kendall, 1990; Renaud et al., 1990; Thorsteinsson, 1992). One suite of modifications to trawl nets that has been tested successfully in a number of fisheries involves square-mesh panels in codends (Robertson, 1983a; Isaksen and Valdermarsen, 1986; Robertson and Stewart, 1988; Carr, 1989; Suuronen, 1990; Briggs, 1992; Thorsteinsson, 1992; Fonteyne and M'Rabet, 1992; Casey et al., 1992; Walsh et al., 1992). These papers attempted to determine the selective properties of square-mesh panels in codends for benthic species and identified them as possible solutions to release roundfish while retaining a large proportion of the targetted catch.

Given this recent and successful history, the present situation in the Hawkesbury River suggests that square-mesh panels in codends may reduce by-catch, thereby reducing conflict. Our specific goals in this paper were to complete a manipulative field experiment under normal commercial fishing operations to determine the characteristics for retaining prawns and excluding mulloway of two designs of codend which incorporate square-mesh panels.

Materials and methods

This study was carried out in April 1992 on established prawn-trawl grounds in the Hawkesbury River using a commercial prawn trawler (10 m). This fishery uses single-rigged otter-board prawn trawls based on the Florida Flyer design. A single locally designed prawn net with a headline length of 11 m (mesh size 40 mm) was rigged so that the codend could be exchanged. This trawl was used in replicate 30 min tows at approximately 2.5 knots in depths ranging from 2 to 8 m.

The codends used in this experiment measured 50 meshes long (2 m) and were constructed from 40 mm mesh netting (see Fig. 1). They comprised two panels: the anterior panel was 25 meshes long and constructed of 2 mm diameter twisted twine; the posterior panel was 25 meshes long and constructed of 3 mm diameter braided twine. Three designs of codend were examined. The control codend (conventionally used in the Hawkesbury River fishery) was hung such that all meshes were diamond-shaped (Fig. 1(A)). The second codend (referred to as the all-square codend) had the netting cut on the bar such that the whole codend was made up of square-shaped meshes (Fig. 1(B)). The third codend (referred to as the half-square codend) was intermediate between these, with the posterior section of the codend hung with conventional diamond-shaped meshes and the anterior section hung with square-shaped meshes (Fig. 1(C)). We predicted that the latter codend would provide a means for water and swimming fish to escape from the codend through the larger anterior openings.

The three codends were interchanged between tows in a random order so that each codend was used three times per day (total of nine tows per day). Over ten consecutive days during the trawling season when mulloway were in great abundance, we completed a total of 30 replicate tows for each of the three codends. To ensure independence among tows, the location of each tow was randomly selected from the available prawn-trawl locations that were possible under the particular conditions. These locations were determined by

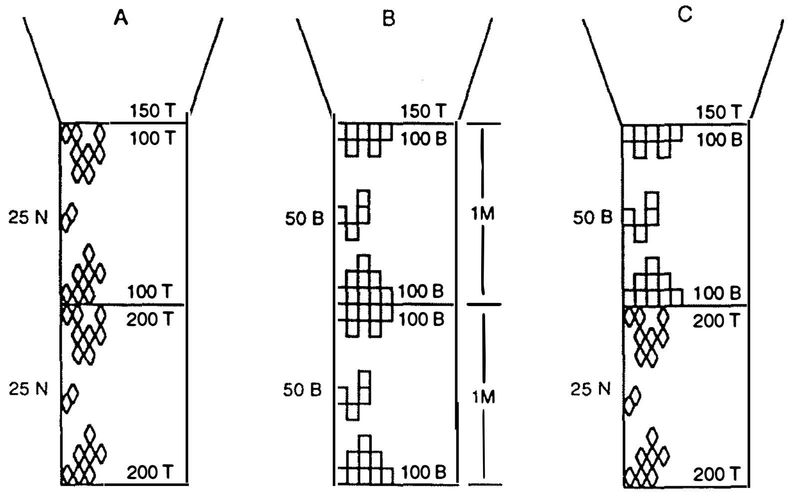

Fig. 1. Diagrammatic representation of codends used in this experiment: (A) control codend; (B) all-square codend; (C) half-square codend (T, transversals; B, bars; N, normals).

the fisher's local knowledge and were dependent upon such factors as the tide and clarity of the water.

After each tow, the codend was emptied onto a tray. All organisms were sorted according to species, the most abundant being prawns, mulloway and catfish (*Euristhmus lepturus*). Data recorded from each tow were: the total weight of prawns, the total weight of by-catch, the weights, numbers and sizes of mulloway (to the nearest 0.5 cm), the weights and numbers of catfish, the numbers and sizes of other commercially and/or recreationally important species (to the nearest 0.5 cm), the numbers of non-commercial/recreational species and the total number of species in the assemblage. All prawns in a

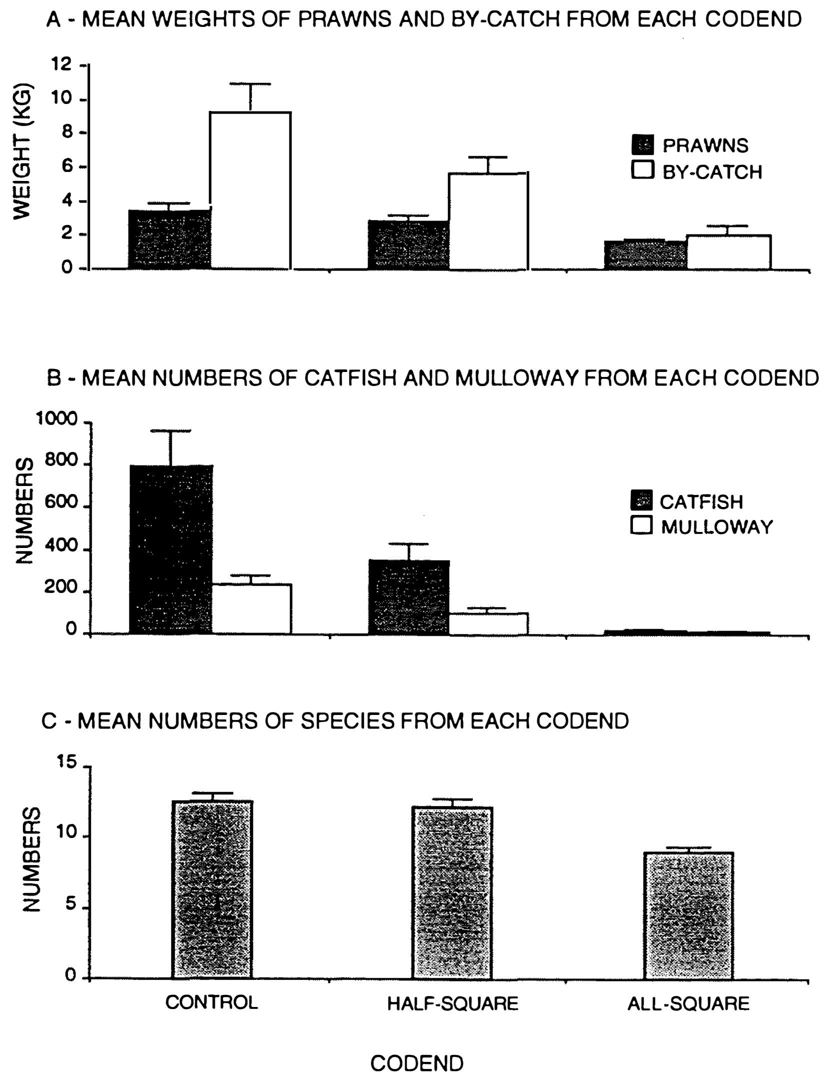

Fig. 2. Differences in mean catches (±SE) (per 30 min tow) of (A) the weights of prawns and all by-catch, (B) the numbers of catfish and mulloway and (C) the numbers of species ($n=30$ for each codend pooled across days).

Table 1(a)
Summaries of F ratios from analyses of variance to determine effects on variables due to fishing with different codends and on different days

Treatment	d.f.	Weight of prawns	Weight of by-catch	No. of mulloway *A. hololepidotus*	No. of catfish *Euristhmus lepturus*	No. of species
Codends (C)	2	21.61*	29.0*	80.65*	65.22*	21.1*
Days (D)	9	6.38*	0.94	1.5	1.38	1.03
C×D	18	1.62	1.45	1.2	1.1	1.31
Residual	60					

To stabilize variances the weights of prawns, by-catch and the numbers of mulloway and catfish were transformed using $\ln(x+1)$. The data for number of species were treated in the raw form.
*Significant ($P<0.01$).

Table 1(b)
Summaries of Student–Newman–Keuls multiple comparisons of the means of each codend for the five variables

Weight of prawns	Control = 1/2 > all square
Weight of by-catch	Control > 1/2 > all square
No. of catfish	Control > 1/2 > all square
No. of mulloway	Control > 1/2 > all square
No. of species	Control = 1/2 > all square

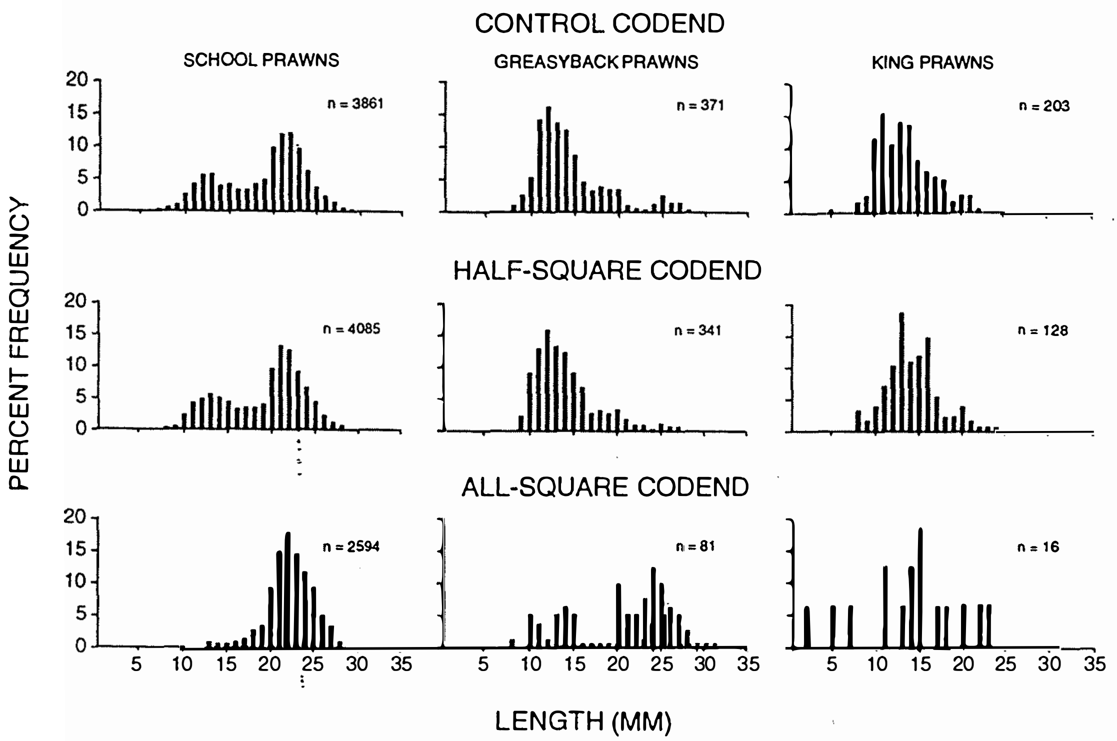

Fig. 3. Length–frequency distributions of school prawns (*Metapenaeus macleayi*), greasyback prawns (*Metapenaeus bennettae*) and king prawns (*Penaeus plebejus*) from each of the three codends.

subsample of the total prawn catch from each tow were measured in the laboratory (to the nearest 1 mm).

Data for all variables were analysed using Cochran's test for homogeneity of variances, transformed if necessary, and then analysed in the appropriate two-factor analysis of variance (see Underwood, 1981). Significant differences detected in these analyses were investigated using Student–Newman–Keuls multiple comparisons of means. Size–frequencies of prawns and mulloway were graphed and compared.

Results

Both the codends with square-mesh panels significantly reduced the weight of by-catch and the numbers of catfish and mulloway (Figs. 2(A) and 2(B),

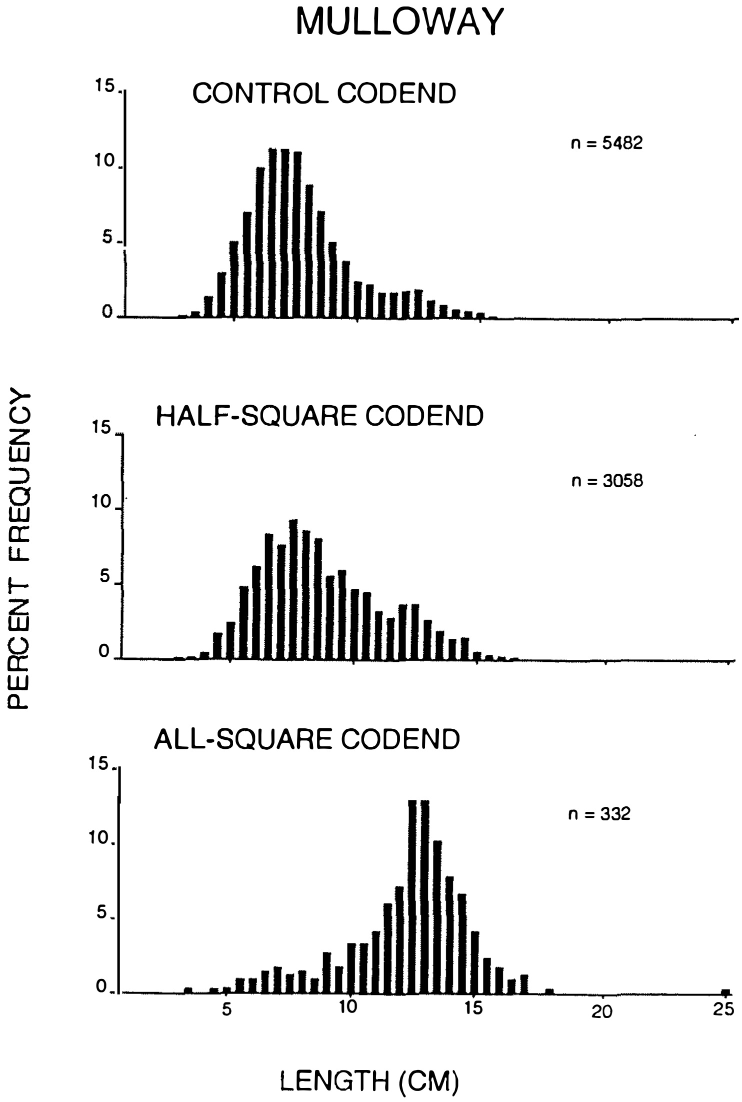

Fig. 4. Length–frequency distributions of mulloway (*Argyrosomus hololepidotus*) from each of the three codends.

and Table 1). The mean numbers of mulloway were reduced by 95% in the all-square codend and by 54% in the half-square codend. The half-square codend did not significantly reduce the numbers of species in the assemblage nor the catches of prawns, although the mean weight of prawns was 16% lower in this codend (Figs. 2(A) and 2(C), and Table 1). The all-square codend, however, significantly reduced the weights of prawns (difference between means of 52%) and the numbers of species. Of all variables, only the weight of prawns caught was significantly different among days in the experiment (Table 1). No variables displayed significant interactions between type of codend and days of sampling.

School prawns, *Metapenaeus macleayi*, and mulloway were represented by two easily identifiable cohorts in the control and half-square codends (Figs. 3 and 4). The size distributions of these species in the all-square codend showed only the larger of the two cohorts. The size compositions of greasy-back prawns, *Metapenaeus bennettae*, and king prawns, *Penaeus plebejus*, were similar in the half-square and control codends, whereas the all-square codend proportionally caught fewer small prawns (Fig. 3).

Discussion

The data presented above illustrate that codends with square-mesh panels selectively reduced the catch of non-target species (see also Robertson 1983b; Robertson and Stewart, 1988; Arkley, 1990; Briggs, 1992; Fonteyne and M'Rabet, 1992). In addressing possible reasons for these patterns, it is useful to examine various behavioural characteristics which may cause the apparent selectivities of square-mesh panels. Previous studies have shown that fish and invertebrates display different reactions to mechanical stimuli (Watson, 1976; Wardle, 1983, 1989; Main and Sangster, 1985; Newland and Chapman, 1989). Generally, fish, unlike slower-moving benthic invertebrates, exhibit a herding response to trawls. In an attempt to maintain position with a moving net, fish invariably tire and fall back towards the tapering codend (Wardle, 1983). Chapman (1964) suggested that a possible area of escape for these fish may occur at this point because, as they are herded close together, the balance of the school is upset, initiating an escape response towards the sides of the net. The school may even continue this escape response by attempting to push through the meshes at the sides of the net. Briggs (1992) observed the behaviour of North Sea whiting (*Merlanguis merlanguis*) in a codend with a square-mesh panel and concluded that the fish nosed along the diamond mesh panels of the codend, actively seeking escape. Once they encountered the panel of square-mesh, they were able to pass through the larger openings.

In contrast, the response of benthic invertebrates such as prawns to stimuli from trawled gears appears to be limited (Lockhead, 1961; Main and Sangster, 1985; Newland and Chapman, 1989). Scuba observations by Watson

(1976) indicated that a strong external stimulus (such as the ground chain of a trawl) resulted in penaeid prawns contracting their abdomens ventrally, effectively propelling themselves backwards. This initial escape response was repeated three to five times, after which the prawns attempted to orientate themselves to the seabed using their swimmerets. Because prawns are not capable of maintaining such activity for long, the flow of water generated by the moving trawl quickly forced the prawns against the meshes and they eventually tumbled down the net. Once in the rear of the codend, their retention depended on the mesh-size of the codend rather than any active escape response. Because openings in the meshes in the all-square codend used in the present study were larger than in the control codend, there was less likelihood that smaller individuals could have been retained, thus explaining the relatively small catches and larger sizes of prawns caught. Similarly, any fish that did not escape at the point of codend taper in this codend would likewise be subjected to the same selectivity as the prawns, hence the small numbers of mulloway and catfish retained (Fig. 2). Although the most efficient in excluding mulloway, the all-square configuration is probably economically unacceptable in terms of catching prawns (52% reduction in mean catches) and therefore should not be considered as a viable option for management.

The half-square codend retained less mulloway than the control codend (54% difference in mean catches) with no statistically significant reduction in prawn weights (Fig. 2 and Table 1). This result may be attributed to the differences in behaviour discussed above and differences in hydrodynamic pressure anterior to the diamond-mesh section. Because meshes in the posterior section of the codend are virtually closed, waterflow through the codend is restricted, causing a back-pressure of water to be directed out through the anterior square meshes. Such a movement of water would assist the escape of free-swimming fish. Chapman (1964) labelled this the 'damming phenomenon', and suggested that such a disturbance may stimulate the lateral-line receptors of fish and contribute to their escape responses.

There were no significant differences between the size compositions of prawns and mulloway captured in the half-square and control codends (Figs. 3 and 4). The all-square codend retained only the larger of these organisms, probably because openings in the meshes in the posterior section were larger. There were no interspecific differences in the length–frequencies of the prawns caught during the experiment, suggesting that these three species reacted similarly once inside the net.

This experiment showed that there is great potential for the eventual development of a codend with square-mesh panels that excludes a large proportion of fish (including juvenile mulloway and catfish) while retaining an acceptable amount of prawns. Because Briggs (1992) observed that most fish escape through the first few rows of such panels, a modification to the codends described in the present paper would be to reduce the size of the square-mesh panel in the half-square codend. Such a modification may maintain the escape of fish such as mulloway, while reducing the likelihood that prawns will 'flick' through the open meshes during their initial escape response. Further, because larger fish are more likely to avoid capture initially (because they swim faster), a reduction of the mesh size in the square-mesh panel may enhance the retention of prawns while still excluding small fish.

Although the mulloway-exclusion characteristics of square-mesh panels were apparent, there remains a question surrounding the physical trauma associated with escaping (Main and Sangster, 1988; DeAlteris and Castro, 1992). For example, Briggs (1992) observed that clupeoids lost scales during escape through netting. In addition, fish may also damage fins and gills during movement through square meshes, contributing to overall stress and possibly post-trawl mortality. In two of the few studies which have examined such mortalities, DeAlteris and Reifsteck (1993) found negligible mortalities of fishes that had passed through square-mesh panels, and Main and Sangster (1988) showed that fish passing through square meshes had greater rates of survival than those passing through diamond meshes. Obviously, any future research to refine modifications to codends should include an assessment of such effects.

In this study, we have demonstrated that square-mesh panels have the potential to reduce the incidental capture of juvenile mulloway by the Hawkesbury River prawn-trawl fleet while retaining the majority of prawns caught. Further research needs to be done in refining the designs of these codends so that more juvenile fish are excluded, catches of prawns are maintained and the extent of post-trawl mortalities of excluded fish are assessed.

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Development of by-catch reducing trawl gears in NSW's prawn trawl fisheries.

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DEVELOPMENT OF BY-CATCH REDUCING TRAWL GEARS IN NSW'S PRAWN TRAWL FISHERIES

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ABSTRACT

A recent large-scale, stratified, randomized observer programme onboard NSW's estuarine and oceanic prawn trawlers identified and quantified the catches and by-catches of these fleets. The results led to fishery-specific information concerning the species and quantities of by-catches throughout NSW and so provided an excellent starting point for attempts to reduce unwanted by-catches. This work led to the current project which is testing a variety of modifications to conventional trawls (including various panels, funnels and grids) which aim to reduce the by-catch of juvenile finfish whilst maintaining catches of prawns. Such gear-development work on prawn trawlers is facilitated by the fact that twin and triple-rigged trawl gear and trouser trawls can be incorporated into experimental designs involving control and modified trawls and therefore provide rather straightforward comparisons. This work is mainly concentrated offshore from 2 oceanic locations (Iluka/Yamba in the north and Port Stephens/Newcastle in the south of NSW) and in 2 estuaries (the Clarence River in the north and Botany Bay in the south). We charter commercial vessels that are representative of the fleet and are set up to trawl in the conventional way. The experiments done so far have yielded very promising results with reductions in by-catches of well over 50% being recorded with negligible losses of prawns. We see the involvement of industry in all aspects of this research as a vital pre-requisite to the eventual implementation of the results into the various fisheries.

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INTRODUCTION

A common definition of the term "by-catch" is Saila's (1983) "that part of the gross catch which is captured incidentally to the species towards which there is directed effort". Under such a definition, there are few fisheries in the world which do not have by-catch, making the scope, diversity and history of the issue enormous. In recent years, a great deal of interest in by-catch has focussed on demersal trawl fisheries because they use comparatively non-selective fishing gears and so catch large quantities of a wide range of species.

In some countries and fisheries, some or all of the by-catch from demersal trawling is considered as a "bonus from the sea" and is utilized as a source of protein for human or animal consumption. Recently, however, more negative aspects of this by-catch have been emphasised as the mortality of certain by-catch species is thought to reduce the subsequent sizes of stocks in other fisheries which target such species. These negative effects on interacting fisheries may range from relatively simple effects (such as the direct mortality of juveniles due to trawling and discarding) through to more complex effects on community structure caused by habitat degradation, influences on species interactions and consequent cascading effects throughout the food web. In the last few years, there has been an increased awareness of these problems of by-catch from demersal trawling, making this one of the most important and critical issues facing commercial and recreational fisheries throughout the world.

In Australia, concern about the deleterious impacts of by-catch from prawn fishing began as early as the late nineteenth century when a Royal Commission examined the fisheries of NSW (Macleay et al., 1880). The by-catch from demersal trawling for prawns and fish is still of great concern to a broad cross-section of the community in Australia, particularly commercial fishers other than trawler operators (e.g. fish trappers, set and hand-liners, mesh netters, beach seiners), as well as recreational fishers, conservationists, environmentalists, fisheries managers, scientists and politicians from all levels of government. Of major concern are complaints regarding demersal trawlers catching and discarding large numbers of undersize fish that, when larger, are targeted in other commercial and recreational fisheries. In particular, these claims are made with respect to prawn trawlers working in estuarine and oceanic locations thought to be nursery grounds for important fish.

It is worth noting, however, that not all by-catch is considered undesirable. In NSW we divide by-catches into what is known as trash (including the above-mentioned discarded juveniles) and the so-called "by-product". In the trawl fishery for oceanic eastern king prawns (*Penaeus plebejus* Penaeidae) for example, large quantities of octopus (*Octopus* spp. Octopodidae), squid (*Loligo* spp. Loliginidae), trawl whiting (*Sillago* spp. Sillaginidae) and balmain bugs (*Ibacus* spp. Scyllaridae) are landed and significant domestic and overseas markets have been developed. This "by-product" is usually considered "acceptable" in terms of inter-fishery conflicts because alternative fisheries are negligible.

OBSERVER-BASED QUANTIFICATION OF BY-CATCHES

The first piece of information that is required to understand trawl by-catch concerns descriptions of its quantity and diversity. Whilst the most obvious and valid way to determine this information is for scientific observers to sort, identify, count, measure and weigh by-catches from normal commercial fishing operations, there have been only a few such studies completed in Australia.

The first study of by-catch from prawn nets in Australia was published 90 years ago by Dannevig (1904) who provided data on the numbers, species and marketability of by-catch from a survey of replicate prawn hauls in Sydney Harbour by a commercial fisher under normal operations. He concluded that "all the most serious charges against the sunken prawn-net (that bushels upon bushels of young fish are being killed by the prawn nets and that the latter have been the ruin of the local fisheries - Macleay et al., 1880) have either been based upon an absolute misconception or are otherwise greatly exaggerated .... many unfavourable observations that from time to time have been made with regard to the work in shallow water have been attached to the industry generally, and this is where considerable injustice has been done". These conclusions are consistent with those from our modern-day observer programmes (see below) which show large spatial and temporal variabilities in the identities and quantities of by-catch species.

In 1988 we began a large-scale observer programme to assess by-catches in New South Wales' oceanic and estuarine prawn fisheries in response to claims concerning large mortalities of juvenile fish (Kennelly, 1993). This project involved onboard observers working alongside commercial trawlers and deckhands to sort, identify, count, measure and weigh the assemblages of species caught during normal fishing operations. This was done out of 4 of the main ports for the offshore fisheries of NSW (see Fig. 1) and in 5 of the 6 estuaries where prawn trawling is permitted. After censusing over 3,500 tows during 3 years, the data from this project was combined with information on the numbers of days fished by various fleets to provide reasonably precise estimates of total by-catches caught by various fleets in different places and times (see Figs. 2 and 3). Seasonal estimates of by-catches in the order of hundreds of thousands up to millions of juvenile finfish were obtained.

An important point concerning these estimates that is often overlooked when discussing trawl by-catch is that, even if all the large numbers of juvenile finfish discarded by prawn trawlers die, this may not have any detectable effect on subsequent stocks of fisheries for these species if most of these juveniles would have died of natural causes anyway as they grew to legal size. Estimates of the natural mortalities of by-catch species, their biomasses, their ages at legal-size and estimates of trawl-induced mortality must all be incorporated to estimate any impacts of trawl by-catch on subsequent stocks for these species. Unfortunately, we have very few estimates of the relevant life-history parameters of key fishes in Australia. In one such attempt, however, Kennelly et al., (1993) estimated that the by-catch of juvenile snapper (*Pagrus auratus* Sparidae) of 350,000 fish in one season in the Botany Bay prawn fishery may represent approx. 60,000 legal-size fish 3 years later. Without an estimate of the relative proportion of the available biomass that these by-catches represent, however, no conclusions are possible. For example, estimates of by-catches of particular species that are of the order of 350,000 fish may be negligible if the biomasses of these fish in these places are in the billions.

The data in Figs. 2 and 3 shows a great deal of variability in by-catches with large quantities only occurring in certain places at certain times. We concluded from this work that such variabilities preclude the establishment of fixed seasonal or localized spatial closures, implying that more flexible closures may be necessary. To advise managers on the most effective times and locations of such closures, however, onboard observers would need to collect data on a regular basis throughout the full spatial range of the fishery. Of course, such large and expensive programmes would be unnecessary if managers could rely on industry for such information, but this is unlikely because fishers may be reticent to restrict their own fishing in order to protect species that are of little or no importance to them.

BY-CATCH REDUCING MODIFICATIONS TO TRAWL GEARS

With fixed spatial and temporal closures unlikely to succeed as a management tool in solving the trawl by-catch problem in NSW, we decided to head in the direction taken by other countries and attempt to develop modifications to trawl gears that may reduce unwanted by-catches whilst maintaining catches of prawns and other acceptable "by-product". This research began a few years ago and we have enjoyed a great deal of success in testing modifications like solid separator grids and square mesh windows in our estuarine and oceanic trawl fisheries.

This work has involved constant and intensive collaboration with fishers so that we can take full advantage of their unique practical knowledge of the relevant gear as it applies in their fisheries. We charter commercial vessels for our field work and employ commercial fishers and netmakers to build our gear. The experiments we use in this research usually involve rather straightforward comparisons of different gears in twin and triple-rigged gear trials. Modified codends are placed in one net and catches from replicate tows are compared with those from conventional, control codends in the other net.

One of the first trials we did showed that the Morrison soft TED, as used in some American fisheries, significantly reduced the amount of by-catch in the New South Wales king prawn fishery by excluding most organisms from codends that were larger than the mesh-size of the TED panel (Andrew et al., 1993, see Fig. 4). This type of TED is also used by certain estuarine prawn trawl fisheries in New South Wales to exclude unwanted jellyfish (*Catostylus mosaicus* Catostylidae) from by-catches.

In one of the few Australian attempts to modify trawl gear to reduce the by-catch of fish that are a similar size as the targeted prawns, we compared conventional codends with designs that incorporated square-mesh panels (Broadhurst & Kennelly, 1994). This work has been quite successful in estuarine (Fig. 5) and oceanic (Fig. 6) fisheries in NSW. These designs took advantage of the different behaviours of prawns and fish when caught in a prawn trawl by providing the swimming juvenile fish avenues of escape before reaching the base of the codend. The results showed that square-mesh panels in codends retained most of the prawns targeted and other by-product and excluded significant numbers of juvenile fish and other unwanted by-catch.

We have also had marked success in trialling the Nordmore Grid (see Fig. 7). With the help of Bjornar Isaksen from Bergen, Norway, we developed some grids and trialled them in our estuarine fisheries. The results were very promising (see Fig. 8) and after just a few weeks of testing, several vessels in these fleets are using the grids to reduce by-catch on a purely voluntary basis. Such involvement and acceptance by industry of these modifications will greatly facilitate the eventual legislation of these modifications.

CONCLUSIONS

Research into more selective trawl gears in Australia has only begun in the past few years but the results have been very encouraging. Our work has shown that it is important to have industry actively involved in any study seeking to reduce by-catches for several reasons: (i) industry are seen to be a driving force in addressing potential problems that other fisheries and the public may derive from the by-catch of large numbers of juvenile fish; (ii) scientists and managers can fully utilize industry's unique practical knowledge of the relevant gear technology as it applies to their fisheries; and (iii) the adoption of new gear modifications into legislation is achieved in a relatively painless and even positive fashion.

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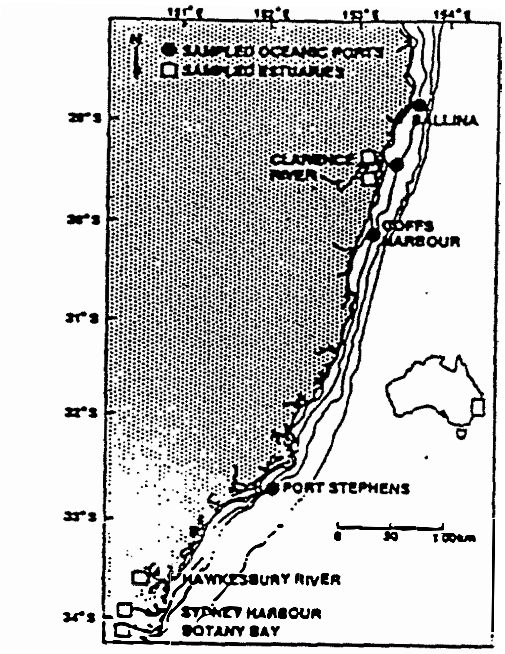

Fig. 1. Location map showing the offshore and estuarine fisheries sampled during the large-scale observer programme.

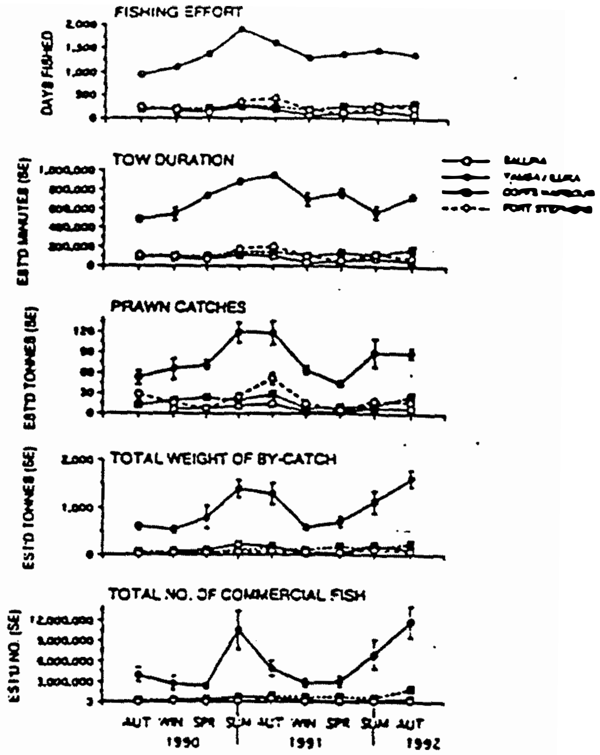

Fig. 2. Extrapolated estimates (derived by combining catch and by-catch rates from the observer work with fishing effort) of tow durations, prawn catches and by-catches from the main oceanic prawn trawl ports in NSW.

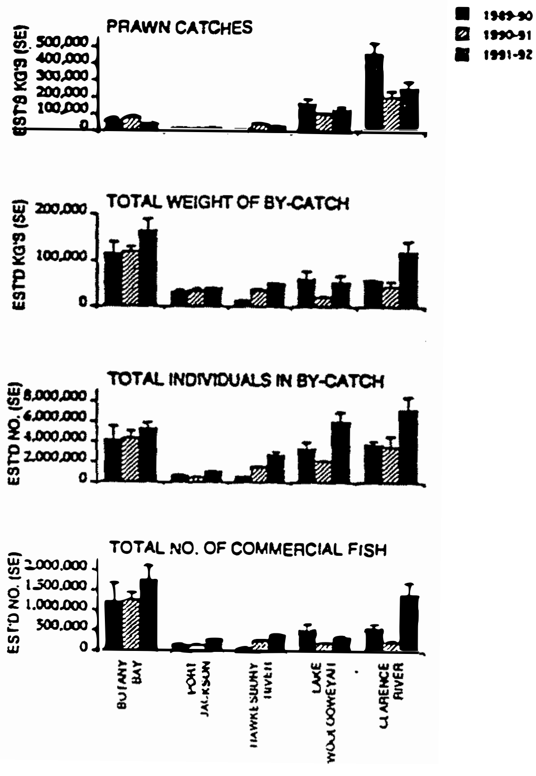

Fig. 3. Extrapolated estimates (derived by combining catch and by-catch rates from the observer work with fishing effort) of prawn catches and by-catches from the main estuarine prawn trawl fisheries in NSW.

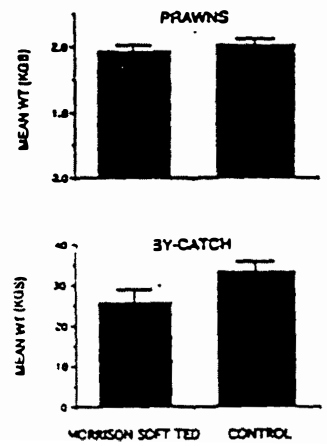

Fig. 4. Prawn catches and by-catches in nets containing the Morrison soft TED compared to control nets.

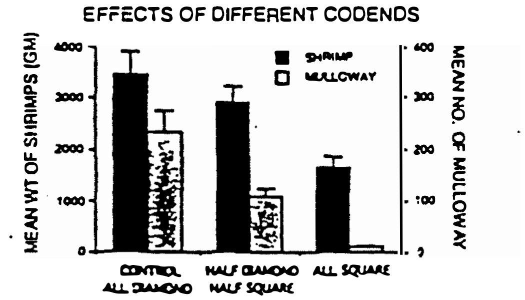

Fig. 5. Prawn catches and by-catches of small finfish in an estuarine fishery using nets that have codends: made entirely of square mesh; containing half square mesh and half diamond mesh; and the control made entirely of diamond mesh.

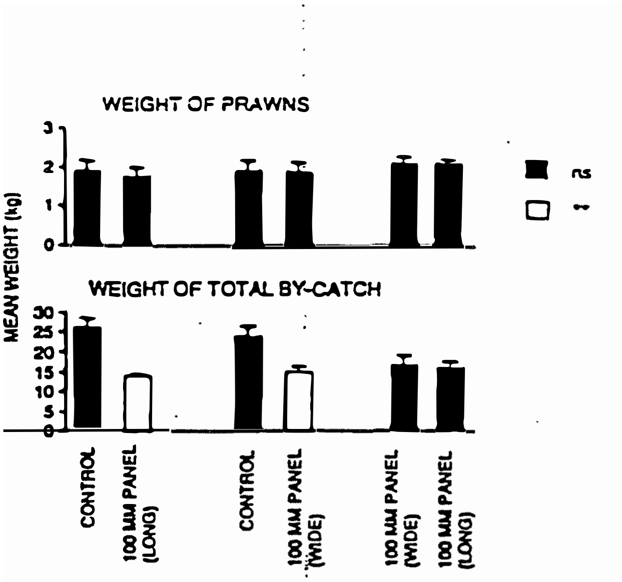

Fig. 6. Prawn catches and by-catches in an oceanic fishery using nets containing 2 types of square mesh window compared to control nets and to each other.

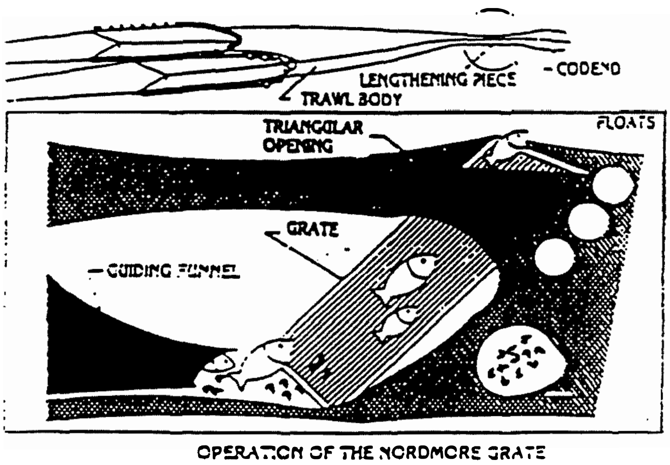

Fig. 7. Schematic representation of the operation of the Nordmore Grid.

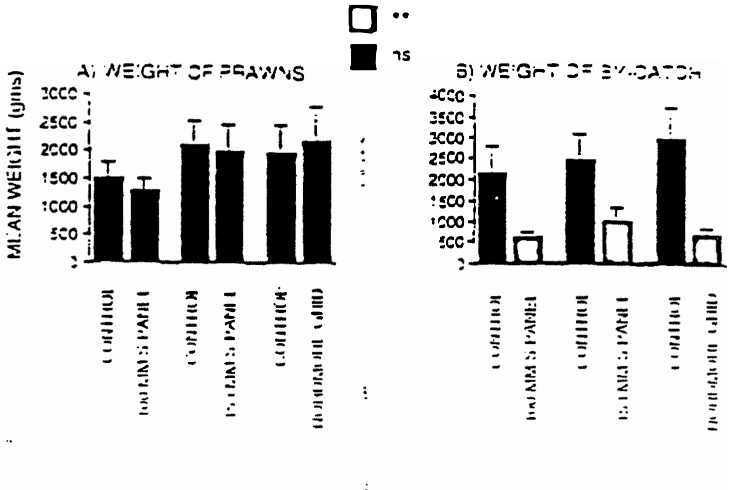

Fig. 8. Prawn catches and by-catches in an estuarine fishery using nets containing 2 types of square mesh window and a Nordmore Grid, each compared to control nets.

The issue of by-catch in Australia's demersal trawl fisheries.

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The issue of bycatch in Australia's demersal trawl fisheries

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Contents

Introduction

A common definition of the term 'bycatch' is Saila's (1983) "that part of the gross catch which is captured incidentally to the species towards which there is directed effort". Under such a definition, there are few fisheries in the world which do not have bycatch, making the scope, diversity and history of the issue enormous. In recent years, a great deal of interest in bycatch has focused on demersal trawl fisheries because they use comparatively non-selective fishing gears and so catch large quantities of a wide range of species (Andrew and Pepperell, 1992; Klima, 1993; Tillman, 1993). This review summarizes the available literature concerning bycatch in Australia's demersal fish and prawn trawl fisheries.

Some fishing gears are very selective in their operation and catch virtually no bycatch (e.g. some purse seine and squid jigging fisheries), but most other gears (fish traps, longlines, droplines, crab pots, angling rods etc.) will catch organisms that are untargeted (Tillman, 1993). A combination of the selective properties of the fishing gear, the skill of the fishers and the place and time of fishing determines the quantity of bycatch that is caught, discarded, damaged and killed. Most fishing gears are somewhat selective in what they catch, but other, less selective gears (e.g. demersal trawling for prawns and fish) have the potential to catch large quantities and a wide diversity of organisms and so cause interactions with other species, other fisheries and therefore other user groups (see also Andrew and Pepperell, 1992; Klima, 1993). Non-selective fishing gears may also affect the target fishery itself when bycatch includes those individuals of a target species which are caught and discarded because they are too small or unworthy to retain. The mortality of such conspecifics during capture and discarding is the major reason for such management measures as mesh-size restrictions on nets and traps and minimum or maximum size limits on retained individuals (Gulland, 1973; Howell and Langan, 1987).

In some countries and fisheries, some or all of the bycatch from demersal trawling is considered as a 'bonus from the sea' and is utilized as a source of protein for human or animal consumption (IDRC, 1982; Peterkin, 1982; Saila, 1983). Recently, however, more negative aspects of this bycatch have been emphasized as the mortality of certain bycatch species is thought to reduce the subsequent sizes of stocks in other fisheries which target such species (e.g. Gordon, 1988; Foldren, 1989; Cooper, 1990; Ohaus, 1990; Klima, 1993). These negative effects on interacting fisheries may range from relatively simple effects (such as the direct mortality of juveniles due to trawling and discarding) through to more complex effects on community structure caused by habitat degradation, influences on species interactions and consequent cascading effects throughout the food web. In the last few years, there has been an increased awareness of these problems of bycatch from demersal trawling, making this one of the most important and critical issues facing commercial and recreational fisheries throughout the world (Klima, 1993; Tillman, 1993).

In Australia, concern about the deleterious impacts of bycatch from prawn fishing began as early as the late 19th century when a Royal Commission examined the fisheries of New South Wales (Macleay *et al.*, 1880). The bycatch from demersal trawling for prawns and fish is still of great concern to a broad cross section of the community in Australia, particularly commercial fishers other than trawler operators (e.g. fish trappers, set and hand-liners, mesh netters, beach seiners), as well as recreational fishers, conservationists, environmentalists, fisheries managers, scientists and politicians from all levels of government. Of major concern are complaints regarding demersal trawlers catching and discarding large numbers of undersize fish that, when larger, are targeted in other commercial and recreational fisheries. In particular, these claims are made with respect to prawn trawlers working in estuarine and oceanic locations thought to be nursery grounds for important fish (Andrew and Pepperell, 1992). The literature concerning trawl bycatch in Australia has grown markedly since the early 1970s and is diverse in the kinds of information derived and the methods used. These papers can be separated into several categories: studies that describe the abundances, diversities and utility of bycatches; studies of the fate of discarded organisms; tests of impacts on epibenthic habitats and assemblages of fishes; and the development of modified gears and fishing practices designed to minimize bycatch. Table 1 contains a summary of these papers by listing the location (Fig 1), key issues examined and the main conclusions.

Identifying and quantifying bycatches

COMMERCIAL OBSERVER SURVEYS

The first piece of information that is required to understand trawl bycatch concerns descriptions of its quantity and diversity (Klima, 1993; Martinez *et al.*, 1993). Whilst

Table 1. Summaries of papers examining bycatch from demersal trawling in Australia

Main issues examined	Fisheries examined (map ref.)*	Main conclusions	References
Identifying and quantifying bycatches			
Commercial observer surveys			
Recreational vs. professional	Sydney Harbour NSW (A)	Bycatches variable. Impacts cannot be generalized	Dannevig (1904)
Bycatch of turtles	Northern Prawn Fishery (B)	Turtle bycatch insufficient to warrant concern	Poiner *et al.* (1990)
Recreational and commercial vs. trawling	Estuarine (A) and Oceanic (C) NSW	Large bycatches of important fish. Highly variable bycatches	Kennelly (1993)
Recreational vs. trawling	SW Australia – prawn and scallop (D)	Significant bycatch of some species. Unlikely to affect sustainable yield	Laurenson *et al.* (1993)
Fishery-independent surveys			
Effects of time of day, tide and location	Moreton Bay, Qld (E)	Large variabilities. Most associations seemed to be random	Stephenson *et al.* (1982a,b)
Quantifying faunal assemblages	Oceanic Qld and Great Barrier Reef (F)	Nearshore, midshelf and inter-reef assemblages were identified	Cannon *et al.* (1987), Jones & Derbyshire (1988), Dredge (1989a,b), Watson and Goeden (1989), Watson *et al* (1990)
Identifying and quantifying bycatches	SW Australia – prawn and scallop (D).	150 species identified, 39 were commerically important	Laurenson *et al.* (1993)
Effects of salinity and location	Hawkesbury R. NSW (A)	Changes in assemblages correlated with salinity and distance upstream	Gray *et al.* (1990), Gray and McDonall (1993)
Designing surveys of bycatch assemblages	Oceanic NSW (C)	Optimal designs for surveys of bycatch assemblages	Kennelly *et al.* (1993b)
Assessing impacts on interacting fisheries			
Interactions between fish trawl and trapping	North West Shelf–fish trawl (G)	Fish trawling affected a fish trap fishery via habitat degradation	Sainsbury (1987, 1988, 1991)
Changes in assemblages after years of trawling	Gulf of Carpentaria (H), Torres St. (I)	Species-specific fluctuations in abundances and a decrease in diversity	Rainer and Munro (1982), Rainer (1984), Poiner and Harris (1986), Harris and Poiner (1991)
Effects of trawling on whiting stocks	Moreton Bay, Qld (E)	Large bycatches of winter whiting had no lasting effect on stock size	Maclean (1972)

Table 1. *Continued*

Main issues examined	Fisheries examined (map ref.)*	Main conclusions	References
Effects of prawn trawling on fish populations	Albatross Bay, Gulf of Carpentaria (H)	Total bycatch estimated to be less than 10% of standing stock	Blaber *et al.* (1990)
Effects of beam trawling on fish populations	Moreton Bay, Qld (E)	River perch numbers may be affected. Bream not affected	Hyland (1985)
Changes in areas open and closed to trawling	Hawkesbury R. NSW (A)	No significant effects of trawling	Gray *et al.* (1990)
Changes in areas open and closed to trawling	SW Australia – prawn and scallop (D)	Smaller numbers in untrawled areas compared with trawled areas	Laurenson *et al.* (1993)
Incorporating natural mortalities and growth rates to assess impacts	Estuarine NSW (A)	Bycatch of 350 000 juvenile snapper may represent 60 000 legal-size fish 3 years later	Kennelly *et al.* (1993a)
Effects on habitats and benthic assemblages			
Effects of fish trawling on habitats and consequences for fish assemblages	North West Shelf-fish trawl (G)	Trawling led to decreases in sponges and other benthos which correlated with changes in fish assemblages	Sainsbury (1991)
Review of impacts of trawling on habitats	Australia-wide review	Very few studies done but potential for significant impacts noted	Hutchings (1990)
Changes in macrobenthos due to trawling	Botany Bay, Estuarine NSW (A)	No detectable alteration in habitats	Gibbs *et al.* (1980)
Habitats in areas open and closed to trawling	SW Australia – prawn and scallop (D)	Physical effects of trawling were short-lived	Laurenson *et al.* (1993)
The fate of discards and consequences for food webs			
Experiments to quantify the fate of discards	Moreton Bay, Qld (E) and Torres St. (I)	Discard survival was low but higher for crustaceans than fish. Trawling moves large amounts of food from the bottom to the surface. This affects feeding and abundances of scavengers on the surface (sea-birds), in mid-water (sharks, dolphins) and on the bottom (rays, crabs)	Wassenberg and Hill (1987, 1989, 1990, 1993), Hill and Wassenberg (1990), Blaber and Wassenberg (1989), Harris and Poiner (1990)
Predation on prawns by bycatch species	Albatross Bay, Gulf of Carpentaria (K)	Large bycatches of species that eat prawns may enhance prawn stocks	Salini *et al.* (1990), Brewer *et al.* (1991)

Utilization			
Observer programme to assess potential utilization of bycatch species	Northern Prawn Fishery (B)	Some species landed. Additional 43 species have market potential	Pender and Willing (1989, 1990), Willing and Pender (1989), Ramm *et al.* (1990), Pender *et al.* (1992a,b)
Economic returns from bycatch	Oceanic NSW (C)	Large markets for octopus, squid, whiting, balmain bugs	Kennelly *et al.* (1993a)
Unusual markets for bycatch	Oceanic Qld (F)	Sea-snakes for snakeskin fashion products. Pipehorses as aphrodisiac	Haysom (1985)
Management alternatives			
Closures to trawling			
Effectiveness of large spatial closures	North West Shelf-fish trawl (G)	Closures cancelled effects of trawling	Sainsbury (1991)
Observer surveys to estimate bycatches	Estuarine (A) and Oceanic (C) NSW Northern Prawn Fishery (B)	Large spatial and temporal variabilities in bycatch preclude confident setting of closures	Dannevig (1904), Pender *et al.* (1992a,b) Kennelly (1993)
Development of more selective trawl gears			
Mono- and multifilaments trawls	Moreton Bay, Qld (E)	Few significant effects. Multifilament caught more small prawns and fewer sand crabs	Sumpton *et al.* (1989)
The Julie Anne semi-demersal fish trawl	Northern Fish Trawl fishery (J)	Footrope raised off bottom resulted in 43% of the bycatch	Mounsey and Ramm (1991)
Effects of long sweeps on trawls	Oceanic NSW (C)	Long sweeps herded whiting and flathead into trawls	Andrew *et al.* (1991)
Trial of the Morrison soft TED	Oceanic NSW (C) Moreton Bay Qld (E)	Excluded most individuals from the cod end that were larger than the mesh size in the TED panel	Andrew *et al.* (1991), Robins-Troeger (1994)
Trials of 'AusTED' – includes a flexible grid	Moreton Bay (E) and Oceanic Qld (F)	Reduced bycatch of rays and turtles with no significant prawn loss	Mounsey *et al.* (in press) Robins-Troeger *et al.*
Soft TEDs voluntarily used by industry	Estuarine NSW (A)	Used by commercial trawlers to reduce bycatch of jellyfish	Kennelly *et al.* (1993a)
Trials of square mesh panels in cod ends	Hawkesbury R. NSW (A)	Reduced bycatch of juvenile fish with negligible loss of prawns	Broadhurst and Kennelly (1994)

*All are prawn fisheries unless otherwise noted.

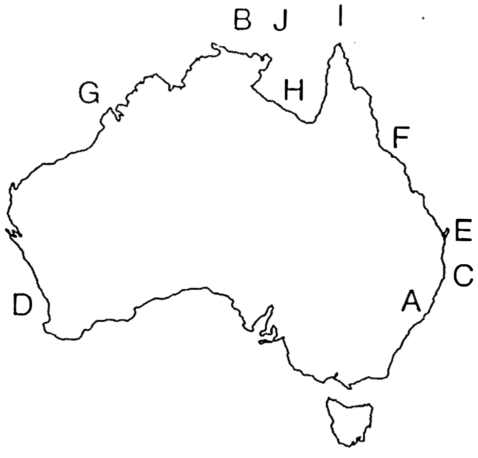

Fig. 1. Location of the study areas examined by papers dealing with demersal trawl bycatch in Australia. Letters refer to references in Table 1.

the most obvious and valid way to determine this information is for scientific observers to sort, identify, count, measure and weigh bycatches from normal commercial fishing operations, there have been only a few such studies completed in Australia.

The first study of bycatch from prawn nets in Australia was published 90 years ago by Dannevig (1904) who provided data on the numbers, species and marketability of bycatch from a survey of replicate prawn hauls in Sydney Harbour by a commercial fisher under normal operations. He concluded that "all the most serious charges against the sunken prawn-net (that bushels upon bushels of young fish are being killed by the prawn nets and that the latter have been the ruin of the local fisheries) have either been based upon an absolute misconception or are otherwise greatly exaggerated . . . many unfavourable observations that from time to time have been made with regard to the work in shallow water have been attached to the industry generally, and this is where considerable injustice has been done". These conclusions are consistent with those from modern-day observer programmes (see below) which show large spatial and temporal variabilities in the identities and quantities of bycatch species.

Recent surveys of demersal trawl bycatch onboard commercial vessels have been done in the Northern Prawn Fishery to examine the potential utilization of bycatches (discussed later) and the incidental capture and mortality of sea turtles (Poiner *et al.*, 1990). The subject of the latter study is a particularly controversial issue in American prawn fisheries where trawl nets now have to include authorized TEDs (turtle exclusion devices – Seidel, 1993). Poiner *et al.* (1990) showed that 4114 (± 1369 SE) sea turtles were estimated to have been in the bycatch of the Northern Prawn Fishery during 1988, of which only 247 (± 90 SE) were estimated to have been drowned. The conclusion was that the mortality of sea turtles through prawn trawl bycatch in this fishery did not warrant concern.

Another observer programme to assess bycatches was done in New South Wales' oceanic and estuarine prawn fisheries in response to claims concerning large mortalities of juvenile fish (Kennelly, 1993; Kennelly *et al.*, 1993a). After censusing over 3500 tows during 3 years, this project provided reasonably precise estimates of total bycatches caught by various fleets in different places and times. Seasonal estimates of bycatches in the order of hundreds of thousands of juvenile snapper (*Pagrus auratus* Sparidae), sea bream (*Acanthopagrus australis* Sparidae) and mulloway (*Argyrosomus hololepidotus* Sciaenidae) were obtained. The data show a great deal of variability in bycatches with large quantities only occurring in certain places at certain times.

Another observer programme was done in the trawl fishery for saucer scallops (*Amusium balloti* Pectinidae) and western king prawns (*Penaeus latisulcatus* Penaeidae) off south western Australia (Laurenson *et al.*, 1993). This study sampled commercial catches over a 12 month period and estimated that of 354 tonnes of fauna caught by trawlers during the year, 109 tonnes were target species, 21 tonnes of bycatch were retained for sale and 224 tonnes of bycatch were discarded. Of the common bycatch species, only the blue manna crab (*Portunus pelagicus* Portunidae) and southern school whiting (*Sillago bassensis* Sillaginidae) were of recreational importance and a stock assessment showed that the bycatch of whiting was not likely to affect its estimated sustainable yield.

Whilst the quantification of bycatches is the first logical step in examining this issue, and direct onboard quantification of bycatches is the best way to get this information, it is surprising that the documented existence of this issue for over 100 years in Australia has resulted in so few observer-based programmes. This is not just an Australian deficiency, as this form of bycatch characterization is rare throughout the world. Clearly, many more such programmes should be done on a fishery-by-fishery basis before we can appreciate the full nature and scope of bycatch from demersal trawling (Klima, 1993; Martinez *et al.*, 1993).

FISHERY-INDEPENDENT SURVEYS

The most common way that fishery scientists have quantified bycatch from demersal trawling in Australia has been through research vessels or chartered commercial vessels doing fishery-independent surveys. While the data generated from such work do not necessarily represent normal fleet operations, they do supply useful information on the identities and quantities of bycatches from the same fishing grounds. The main utility of these surveys, however, comes from using the relatively non-selective nature of demersal trawl gear as a sampling tool to study the distributions and abundances of species in these assemblages.

Several studies have been done in Queensland prawn fisheries which describe patterns in fish assemblages that are in bycatches. Stephenson *et al.* (1982a,b) described the bycatch fauna in Moreton Bay and their associations with time of day, tide and location. Large variabilities were evident and the authors concluded that most interactions appeared to be random variations rather than due to any particular co-variable. Cannon *et al.* (1987), Jones and Derbyshire (1988), Watson and Goedon (1989), Dredge (1989a,b) and Watson *et al.* (1990) used trawl surveys to quantify patterns in faunal assemblages off the coast of Queensland and the Great Barrier Reef. Discrete 'nearshore', 'mid-shelf' and 'inter-reef' assemblages were identified in several of these papers. Laurenson *et al.* (1993) did some trawl surveys off the coast of south-western Australia and identified some 150 species of fish, sharks, rays and invertebrates. Of these, 39 species were recorded from commercial landings and only five were taken in any quantity. Gray *et al.* (1990) and Gray and McDonall (1993) examined fluctuations in bycatches from a prawn-trawl survey in the Hawkesbury River, New South Wales over different years and across various salinity regimes. They showed differences in assemblages which correlated with position in the river and the salinity of different areas. Another study completed in New South Wales made use of prawn-trawl gear as a means for estimating the relative abundances of demersal fauna in offshore grounds (Kennelly *et al.*, 1993b) and provided information on the optimal design for stratified, randomized surveys of these assemblages.

By quantifying the marked spatial and temporal variabilities in the abundances of various bycatch species, these various papers highlight the value of demersal trawl gear in sampling these benthic assemblages. It is ironic that such value is a result of the same, non-selective nature of the gear that causes conflict with other users.

Assessing impacts on interacting fisheries

As mentioned above, the first prerequisite for understanding the fishery-interaction issue of bycatch involves its description and quantification (Klima, 1993), but these do not determine the actual impacts that these bycatches have on other fisheries. Estimating cause-and-effect relationships between bycatches in trawl fisheries and stock sizes in other fisheries is very difficult and few estimates of such impacts have been made. The most common method used in Australia to assess impacts involves using standardized gears and sampling methodologies in fishery-independent surveys. Data from this work are used to detect changes in bycatches and assemblages in areas and times that may be open or closed to trawling and so provide some direct evidence of potential impacts.

The most thorough attempt to assess impacts of trawling on interacting fisheries in Australia is the assessment of the impacts between the Northwest Shelf demersal fish trawl fishery, epibenthic habitats and a nearby fish trap fishery (Sainsbury, 1987, 1988, 1991). Not only was the study described in these papers one of the few to examine a causal relationship between trawl bycatch and an interacting fishery, it was also one of the few studies of trawl bycatch in Australia that examined a fish trawl fishery – most other studies have focused on prawn trawling. The methods involved comparisons of historical records, trawl surveys before and after commercial trawling, in areas closed and open to trawling, and underwater video assessments of the impact of trawling on the epibenthic habitat. The results showed that species of tropical snappers (*Lethrinus* spp. Lutjanidae), which were more common in areas with large epibenthic organisms such as sponges etc., were also the target species of the fish trap fishery and in smaller abundances in areas where domestic and foreign fish trawlers operated. In these latter areas, the benthic habitat was modified such that there were far fewer epibenthic organisms and the fishes which dominated were threadfin bream (*Nemipterus* spp. Nemipteridae) and lizard fish (*Saurida* spp. Synodontidae). It appeared that trawling modified the habitat and fish assemblages of these areas and thus affected the success of the fish trap fishery. This hypothesis was supported in a subsequent adaptive management experiment which compared assemblages in trawled areas with those in areas that were closed to trawling. Sainsbury (1991) summarizes the reasons why this empirical study was possible in this particular fishery: the species involved had quite short life spans and hence short reaction times to changes in management; close management control was possible, facilitating the implementation of closures; the fish trawl fishery was of low value whilst the trap fishery was of high value; the fleet had alternative fishing options during closures; and there were large areas available for closures.

Another study which used survey data to assess possible impacts of trawl bycatch was done in the Gulf of Carpentaria prawn-trawl fishery and compared stratified randomized surveys done before the start of commercial prawn trawling with data collected in similar ways 20 years later (Rainer and Munro, 1982; Rainer, 1984; Poiner and Harris, 1986; Harris and Poiner, 1991). The results showed increases in abundances of 12 taxa of fish, decreases in 18 taxa and in the overall diversity of assemblages.

Other, smaller-scale studies also have used survey data to assess impacts of trawl bycatch but have suffered from being correlative in their approach, lacking proper controls or being pseudoreplicated (*sensu* Hurlbert, 1984). Maclean (1972) described a study of the catch and bycatch of the Moreton Bay prawn fishery and found that large bycatches of winter whiting (*Sillago maculata* Sillaginidae) did not appear to have any lasting effects on stock size. Blaber *et al.* (1990) found from stratified randomized surveys in the Gulf of Carpentaria that large bycatches of certain fish species in Albatross Bay could be attributed to a relatively light exploitation of fish populations in the area, despite the presence of a prawn fishery. Estimates of the total annual bycatch of these fish were thought to be less than 10% of the estimated standing stock of 93 000 tonnes. Hyland (1985) found from fishery-independent surveys that a large number of species may be affected by prawn beam-trawling in Moreton Bay. In particular, river perch (*Johnieops volgleri* Sciaenidae) was present in the bycatch in large numbers, did not appear to survive discarding well and its abundances had shown a steady decrease over time. In contrast, sea bream (*Acanthopagrus australis* Sparidae) appeared to survive trawling quite well and its abundances did not show long-term declines. In the Hawkesbury River in New South Wales, Gray *et al.* (1990) found no significant differences in quantities and compositions of bycatches from areas that were closed and those that were open to commercial trawling. Laurenson *et al.* (1993) compared one trawled area with one untrawled area in a Leslie or DeLury-type depletion experiment (Ricker, 1958) off south-western Australia using continued trawling over fixed places. They found smaller numbers of key species and all species combined in the untrawled area than in the commercial trawl ground.

The conclusion from these various studies is that estimates of impacts vary in their nature and magnitude. Sainsbury's (1991) work on the Northwest Shelf suggests substantial impacts of fish trawling on the interacting fish trap fishery but other, less empirical studies are not as definitive in their conclusions. In several cases, no impacts were evident but this may have been a result of a lack of proper controls or statistical power rather than a lack of significant impact. Rigorously designed and executed experiments comparing replicated, trawled and untrawled areas before and after fishing offer the best chance of revealing cause-and-effect relationships where they exist.

Another way to estimate potential impacts involves incorporating estimates of bycatch-induced mortalities from observer and survey programmes with life-history information of key species (Kennelly *et al.*, 1993a; Klima, 1993). Even if all the juvenile finfish discarded by prawn trawlers die (see below), this may not have any detectable effect on subsequent stocks of fisheries for these species if most of these juveniles would have died of natural causes anyway as they grew to legal size. Estimates of the natural mortalities of bycatch species, their biomasses, their ages at legal size and estimates of trawl-induced mortality must all be incorporated to estimate any impacts of trawl bycatch on subsequent stocks for these species. Unfortunately, we have very few estimates of the relevant life-history parameters of key fishes in Australia. In one attempt, Kennelly *et al.* (1993a) estimated that the bycatch of juvenile snapper (*Pagrus auratus* Sparidae) of 350 000 fish in one season in the Botany Bay prawn fishery may represent about 60 000 legal-size fish 3 years later. Without an estimate of the relative proportion of the available biomass that these bycatches represent, however, no conclusions are possible. For example, estimates of bycatches of particular species that are of the order of 350 000 fish may be negligible if the biomasses of these fish in these places are in the billions. The use of life-history information with estimates of bycatches requires several assumptions but can be useful in deriving first estimates of potential impacts when only simple observer data are available.

Effects on benthic habitats and assemblages

A more subtle impact of demersal trawling involves indirect effects that it may have on assemblages of species by influencing the structure of benthic habitats (Hutchings, 1990). Sainsbury's (1991) work (discussed above) is one of the few examples of an assessment of this sort of impact and showed that by modifying the benthic habitat in areas through the removal of large epibenthic organisms, trawling affected the abundances and kinds of fish species that occupied those habitats.

Gibbs *et al.* (1980) compared epibenthic assemblages (sampled using grabs) in areas before and after trawling in Botany Bay. The authors concluded that otter trawling caused no detectable alterations to the macrobenthic fauna but the large variabilities inherent in their data may account for these non-significant results. Laurenson *et al.* (1993) compared trawled and untrawled areas off south-western Australia using underwater video equipment and concluded that physical impacts of trawling on the substratum were short-lived. As concluded by Hutchings (1990), there is very little information on the interaction between trawling and benthic communities in Australia, making it a high priority area for future research.

The fate of discards and consequences for food webs

Indirect effects of bycatch from demersal trawling include any cascading effects throughout the food web that may occur as a consequence of catching, discarding and killing large quantities of a wide range of species. It is apparent that impacts on bycatch organisms should have follow-on impacts on those species with which they interact through predation, competition, etc. Consequences of such interactions are difficult to comprehend, let alone quantify, and there exist very few examinations of such effects anywhere in the world. The work done in Australia (chiefly by Wassenberg and Hill), however, constitutes one of the first attempts to unravel some of these complexities.

Studies that quantify trawl bycatch often assume that all discards die as a result of the trauma associated with capture, removal from the water and handling, but there exist very few studies that have quantified such mortalities. Through a varied series of experiments in Moreton Bay and Torres Strait, Wassenberg and Hill (1989, 1990, 1993), Hill and Wassenberg (1990) and Harris and Poiner (1990) quantified rates of mortality of various types of discarded bycatch and the proportions that were eaten by surface, midwater and benthic scavengers. The experiments included comparisons of various exposure times on deck, holding discards in seawater tanks for long periods, tethering baits on the surface, in mid-water and on the bottom, analyses of gut contents and *in situ* videos. The results showed that the survival of discards was quite low, although such factors as sorting time, day versus night, air temperature and tow duration were all thought to affect survival. Crustaceans (crabs, bugs etc.) had a higher survival rate than fish, with over 70% surviving up to 7 days after trawling. The only fish to have a survival that was greater than 30% was the small-toothed flounder (*Pseudorhombus jenynsii* Pleuronectidae). Most of the mortality of discards occurred within the first 3 days after trawling, implying that long-term experiments (over several days – not hours) are required to assess this mortality adequately. After discarding, nearly half the bycatch of fish floated, whilst most crustaceans sank. Floating discards were eaten by birds, sharks and dolphins, but birds tended to avoid large discards. The behaviour of birds and dolphins suggested that they had learnt to follow trawlers, an observation that was supported by their behaviour in areas closed to trawling. Those discards that sank did so quite rapidly, spending only 5–10 min in the water column when they were susceptible to midwater scavengers like sharks. Most of the discarded material that reached the bottom was dead fish, whilst most discards reaching the bottom alive were crustaceans. Once on the bottom, discarded material tended to be eaten by other fish, sharks and crabs but there was no evidence of material being eaten by prawns, the trawlers' target species. Of particular interest in this work was the suggestion that the success of the sand crab (*Portunus pelagicus* Portunidae) fishery in Moreton Bay may owe something to the supply of large quantities of discarded trawl bycatch to these benthic scavengers (Wassenberg and Hill, 1987). Similarly, Blaber and Wassenberg (1989) note that the three major species of sea-birds in Moreton Bay primarily depend on food from trawler discards, with the pied cormorant possibly consuming 13.7% of the total fish bycatch.

Two other papers suggested another indirect interaction of trawl bycatch that receives very little attention. Significant rates of predation by small fishes on prawns (Salini *et al.*, 1990; Brewer *et al.*, 1991) may be reduced by the bycatch and subsequent mortality of these fish by prawn trawlers. If such an interaction were sufficiently large, bycatch from prawn trawlers may actually enhance the size of the target stock.

The conclusions from these studies are that trawling results in the movement of large amounts of food from the bottom of the sea to the surface and that this affects the feeding behaviour and eventually the abundances of surface, midwater and benthic scavengers. Despite a lack of human utilization of trawler discards in Australia (discussed below), it is obvious that other organisms in the sea do use this material. Throughout the world, research on the subtle impacts that trawl bycatch may have on the food web is very much in its infancy (Tillman, 1993) and more work along the lines described above needs to be done before we can fully appreciate the scope of such interactions.

Utilization

Some of the international literature on the bycatch of prawn fisheries has emphasized the waste of dumping large quantities of edible protein at sea, especially in or near the waters of developing countries where protein is in short supply (IDRC, 1982; Saila, 1983; Gulland and Rothschild, 1984). Despite this large wastage, substantial utilization of bycatch does occur in many of the world's trawl fisheries (e.g. Grantham, 1980;

Peterkin, 1982; references in Andrew and Pepperell, 1992). A combination of economic factors and limited storage facilities on vessels inhibit greater use of bycatch in many fisheries because the target prawn and fish species are more valuable than bycatches (e.g. Silas *et al.*, 1984; Chong *et al.*, 1987). Further, factors such as the varied species composition of bycatches and the toxicity of some species limits the development of fish meal industries where consistent oil content and protein composition are required (see also IDRC, 1982). Despite such problems, increased use of bycatch is predicted to be an important area of research and development in the future, especially in waters near developing nations.

In Australia, quite substantial profits already come from the bycatch of some fisheries. A recent study focused on potential products and markets from the bycatch of the Northern Prawn Fishery (Pender and Willing, 1989, 1990; Willing and Pender, 1989; Ramm *et al.*, 1990; Pender *et al.*, 1992a,b). These papers described a 3 year programme which assessed the distributions, abundances, size compositions and potential utilization of bycatch species. They identified that only certain valuable species were currently retained for domestic markets (bugs, squids, snappers, emperors, large mackerels, large cods and sharks), with the rest of the bycatch discarded at sea. Some 43 species of fish, sharks, crustaceans and molluscs were identified as having commercial potential, however, with estimated landings of 15 300 tonnes during 1988. Clearly, more diverse markets for such products need to be developed. Haysom (1985) mentioned two quite unusual markets for trawl bycatch species in the Queensland prawn fishery where sea snakes (*Hydrophis elegans* Hydrophidae) are landed for sale in the snakeskin fashion market and dried red-and-gold pipehorses (*Solegnathus dunckeri* Syngnathidae) are sold in Asia as an aphrodisiac.

In the trawl fishery for oceanic eastern king prawns (*Penaeus plebejus* Penaeidae) in New South Wales, large quantities of octopus (*Octopus* spp. Octopodidae), squid (*Loligo* spp. Loliginidae), trawl whiting (*Sillago* spp. Sillaginidae) and balmain bugs (*Ibacus* spp. Scyllaridae) are landed and significant domestic markets have been developed (Kennelly *et al.*, 1993a). Whilst such bycatch is usually considered 'acceptable' in terms of inter-fishery conflicts because alternative fisheries are negligible, these species are still subject to the same problems of over-fishing facing any exploited stock.

Compared with the situation overseas, there is a lack of literature dealing with the utilization of trawl bycatch in Australia. Despite this, conclusions from the studies mentioned above are that the potential for economic use of Australia's trawl bycatch is large, diverse and, with the exception of only a few cases, unrealized. This is clearly one aspect of the trawl bycatch issue in Australia which should attract the future attention of researchers, managers and markets.

Management alternatives

So far I have concentrated on the work that has been done to quantify, describe, characterize and understand the issue of bycatch from demersal trawling in Australia. The above summaries suggest that we have at least some appreciation of the issues and problems, but there have been few studies that have examined ways to solve the problems. Fisheries managers have several choices available that can alleviate problems of bycatch from demersal trawling. One of these involves using bycatch for consumption by developing new markets for these species (described above). Unfortunately this will not solve fishery-interaction issues where the bycatch and mortality of juvenile fishes are seen as causing significant impacts on other fisheries. Publication of results showing bycatches numbering in the hundreds of thousands of juvenile fish per year per fleet leads to strong protests from other commercial and recreational fisheries and these occur despite a lack of information concerning post-trawl mortalities of these discards, their natural mortalities, their overall biomasses and therefore the actual impacts of these bycatches. The various tools which may be used to solve fishery-interaction issues can be broadly categorized as involving either closures to trawling or more selective trawl gears and fishing practices.

CLOSURES TO TRAWLING

The use of closures to trawling to alleviate bycatch problems is considered by trawl fishers to be a harsh management strategy because it involves reducing the harvest of the fishery's target species in those places and times of closures. However, it is clearly the most effective means for stopping any bycatch problems because ceasing trawling ensures no bycatch nor habitat degradation in those places and times that are closed. A problem is that trawling effort may increase in those areas and times outside particular closures, effectively negating some or all of the desired effects of the management strategy. Sainsbury's (1991) work in the Northwest Shelf Fishery examined the effectiveness of large spatial closures and showed that impacts of trawl bycatch on epibenthic habitats and associated assemblages of fish do not occur in areas where trawling is stopped. As summarized earlier, however, the conditions that permitted such large-scale closures were unique to this region and may not be applicable elsewhere, particularly in regions where prawn and fish trawl fisheries are extremely valuable and where alternative fisheries do not exist or are themselves under excessive pressure.

The chief problem with closures as a generalist solution to problems of trawl bycatch lies in being able to identify where and when such closures should be implemented without closing off so much of the target fishery that it becomes uneconomic. As noted earlier, very few data sets exist which describe the bycatch of trawlers operating under normal conditions but these few document quite significant variabilities in the timing and location of large bycatches of juveniles of important species (e.g. Dannevig, 1904; Pender *et al.*, 1992b; Kennelly, 1993). Such variabilities preclude the establishment of fixed seasonal or localized spatial closures, implying that more flexible closures may be necessary. To advise managers on the most effective times and locations of such closures, however, onboard observers would need to collect data on a regular basis throughout the full spatial range of the fishery. Of course, such large and expensive programmes would be unnecessary if managers could rely on industry for such information, but this is unlikely because fishers may be reticent to restrict their own fishing in order to protect species that are of little or no importance to them.

DEVELOPMENT OF MORE SELECTIVE TRAWL GEARS

Another suite of management strategies that may alleviate the trawl bycatch issue involves the development and implementation of more selective gears and fishing practices which are designed to minimize the bycatch and mortality of unwanted organisms. Unfortunately, development of these methods in Australia is very much in its infancy as compared with the substantial amount of work done overseas (e.g. Seidel, 1975; Wardle, 1983, 1989; Watson, 1989; Kendall, 1990; Isaksen *et al.*, 1992).

Sumpton *et al.* (1989) compared catches and bycatches from prawn trawls made of mono- and multifilament netting in the Queensland prawn fishery. The multifilament nets caught more small prawns and less sand crabs than the monofilament nets, but there were no other significant differences in bycatches. In the Northern Fish Trawl Fishery, Mounsey and Ramm (1991) described the development of the Julie Anne semi-demersal fish trawl which was found to catch 43% of the bycatch and only 3% of the epibenthos caught in a conventional trawl. This modified trawl involved raising the footrope of the trawl off the bottom and raising the headrope of the trawl.

Andrew *et al.* (1991) described an experiment which assessed the effects of long sweeps in herding fish into prawn trawls. It was found that these wires which stretch from otter boards to the nets herded red spot whiting (*Sillago bassensis* Sillaginidae) and sand flathead (*Platycephalus caeruleopunctatus* Platycephalidae) but not king prawns (*Penaeus plebejus* Penaeidae), balmain bugs (*Ibacus* spp. Scyllaridae) or other species.

Andrew *et al.* (1993) showed that the Morrison soft TED, as developed and used in some American fisheries, significantly reduced the amount of bycatch in the New South Wales king prawn fishery by excluding most organisms from cod ends that were larger than the mesh-size of the TED panel. This type of TED is also used by certain estuarine prawn trawl fisheries in New South Wales to exclude unwanted jellyfish (*Catostylus mosaicus* Catostylidae) from bycatches (Kennelly *et al.*, 1993a). Robins-Troeger (1994) also describes trials of the Morrison soft TED in Moreton Bay, Queensland, and concluded that the effects of such a modification on prawn retention and bycatch exclusion were highly variable but that the panel worked well for large rays and turtles. Recently, Mounsey *et al.* (in press) and Robins-Troeger *et al.* (in press) describe the design and field evaluation respectively of the so-called 'AusTED' in Queensland waters (Fig. 2(a)). This device is similar to the grid systems used overseas (e.g. Isaksen *et al.*, 1992) but incorporates a flexible grid. The results showed that, like the Morrison soft TED, the bycatch of large rays and turtles was reduced with no significant loss of prawns. While most organisms are excluded that are larger than the mesh-size used in these TED panels, they have limited success in excluding organisms that are smaller or the same size as the target species. Because the most common target organisms in Australia's trawl fisheries are prawns, and the fishery interaction issue of bycatch concerns juvenile fish that are of a similar or smaller size, simple TED panels are an insufficient solution.

In one of the few Australian attempts to modify trawl gear to reduce the bycatch of fish that are of similar size to the targeted prawns, Broadhurst and Kennelly (1994) compared conventional cod ends with two designs that incorporated square-mesh panels (Fig. 2(b)). These designs took advantage of the different behaviours of prawns and fish when caught in a prawn trawl by providing the swimming juvenile fish avenues of escape before reaching the base of the cod end. The results showed that square-mesh panels in cod ends retained most of the school prawns targeted (*Metapenaeus macleayi* Penaeidae) and excluded significant numbers of juvenile mulloway (*Argyrosomus hololepidotus* Sciaenidae). This gear modification showed great potential and further refinements should enhance prawn retention and exclude even larger numbers of small fish (see also Robertson, 1983; Isaksen and Valdermarsen, 1986; Suuronen, 1990; Walsh *et al.*, 1992).

At the International Conference on By-catch in the Shrimp Industry held in Florida

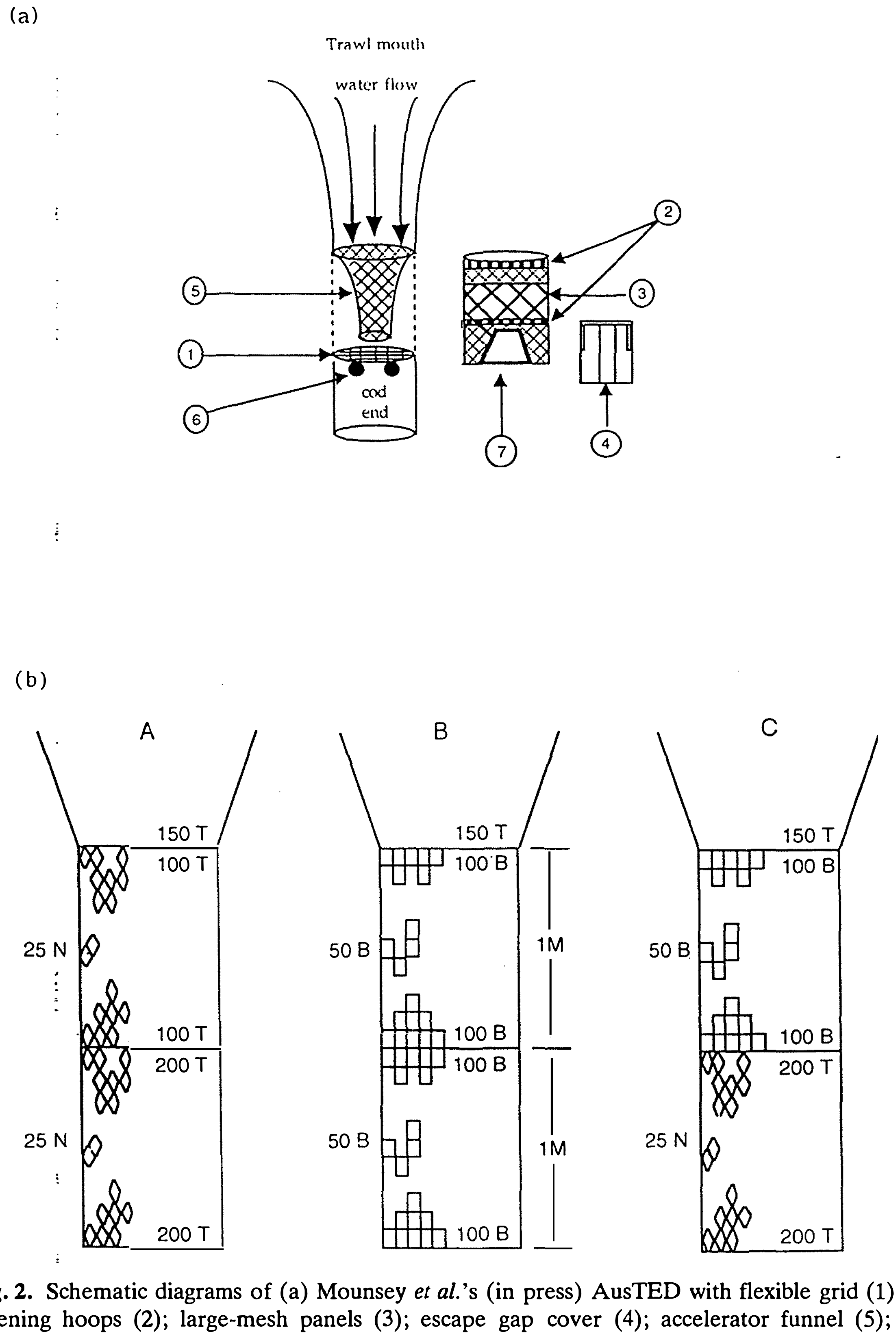

Fig. 2. Schematic diagrams of (a) Mounsey *et al.*'s (in press) AusTED with flexible grid (1); net opening hoops (2); large-mesh panels (3); escape gap cover (4); accelerator funnel (5); grid support floats (6); escape gap (7) and (b) Broadhurst and Kennelly's (1994) cod ends designed to exclude juvenile fish from trawls. Control cod end (A); the all-square cod end (B) and the half-square cod end (C) (T, transversals; B, bars; N, normals).

in 1992, a plethora of different modifications to prawn trawls and fishing practices that reduced bycatches were presented (Berghahn, 1993; Brothers, 1993; Conolly, 1993; Wardle, 1993; Watson, 1993). These included Nordmore grids, TEDs, fish-eyes, short trawl nets, square-mesh panels, sorting machines, short tows, etc. While many of these designs were shown to be effective in their respective fisheries, one of the conclusions from this conference was that the type of modification appropriate for any given fishery depended on the prawns that are being targeted, the type of bycatch that is to be excluded, the nature of the trawling grounds and the fishing practices and vessels employed in the fishery. No one modification was found which would work universally, but the types of modifications that may be appropriate have been well documented. It has also been acknowledged that research along these lines should examine the effects of any trawl modifications on the survival of the excluded bycatch so that effects of damage incurred by escaping fish, for example as they pass through panels, are minimized. This latter problem has only recently begun to attract the attention of gear technologists overseas (e.g. Main and Sangster, 1988; Berghahn *et al.*, 1992), and it is of obvious importance in any future work on trawl modifications.

Research into more selective trawl gears in Australia has only begun in the past few years but the results have been encouraging. At the present time, several large projects are developing trawl modifications with the objective of retaining target species whilst excluding unwanted bycatch. Because of the inherent variabilities in bycatches between fisheries in Australia, this work is being done on a fishery-by-fishery basis, off the east coast of New South Wales (Fig. 1 – A and C), Queensland (E and F) and in the Gulf of Carpentaria (H).

The recent work done in this field in Australia has shown that it is important to have industry actively involved in any study seeking to reduce bycatches for two reasons: (i) industry is seen to be a driving force in addressing potential problems that other fisheries and the public may derive from the bycatch of large numbers of juvenile fish; and (ii) scientists and managers can fully utilize industry's unique practical knowledge of the relevant gear technology as it applies to their fisheries.

Conclusions

Table 1 summarizes the work reviewed in this paper. The chief problems associated with bycatch from demersal trawling in Australia concern conflicts with other fisheries that target species discarded from trawling, i.e. fishery-interaction problems (Klima, 1993; Tillman, 1993). Research into this issue in Australia has concentrated on attempts to describe and quantify the very large quantities and diversities of bycatches. This work has shown marked spatial and temporal variabilities in bycatches, highlighting the need for such descriptive work to be done on a fishery-by-fishery basis. Wassenberg and Hill's work has shown us the complexity that impacts of trawling may have on assemblages and food chains but studies that have actually assessed impacts of trawling on other fisheries varied in their conclusions. Sainsbury's comprehensive study showed significant effects of trawling on another fishery through habitat degradation but the few other studies of fisheries interactions suffered from poor experimental designs. In terms of solving the issue of bycatch, there has been a recent surge in research into more selective trawl gears in Australia and the work done thus far indicates the great potential for such modifications to reduce bycatch problems.

It is clearly necessary to describe and quantify bycatches in specific fisheries (in order to assess whether any problems exist) and the best way to do this is via onboard sampling of bycatches under normal commercial operations. Ninety years ago, Dannevig (1904) published the first observer-based survey of the bycatch of an Australian prawn fishery and it is surprising that, for most fisheries, we still need to obtain such quantitative descriptions of bycatches. But such descriptive work, whilst the first step, is insufficient in solving the problems that arise when these bycatches are described. Once this preliminary descriptive work is done, it is then necessary to test the effectiveness of alternative management strategies which may alleviate any problems that have been detected. Sainsbury's work on the North West Shelf does this for a certain type of management strategy (spatial closures) but the small amount of work done on more selective trawl configurations is unfortunate and obviously needs attention. With the high priority and high profile currently being given to the issue of trawl bycatch in Australia and throughout the world, I am confident that the next 10 years will see substantial advances in solving many of the perceived problems through modifications to trawl gears.

Summary

A common definition of the term 'bycatch' is that part of the gross catch which is captured incidentally to the species towards which there is directed effort. Under such a definition, there are few fisheries in Australia (nor the world) which do not have bycatch, making the scope, diversity and history of the issue enormous. In recent years, the majority of interest in bycatch has focused on demersal trawl fisheries because conventional otter trawls are comparatively non-selective fishing gears and so catch large quantities of a wide range of untargeted species.

In general, the chief problems associated with bycatch from demersal trawling concern conflicts with other fisheries that target species which are discarded by trawlers (i.e. fishery-interaction problems). Research into this issue in Australia has concentrated on attempts to describe and quantify the highly variable but very large quantities and diversities of bycatches from prawn trawling. These descriptive aspects of the issue are prerequisite to identifying, understanding and eventually managing any problems. There has been some research on estimating actual impacts of demersal trawl bycatch on interacting fisheries via fishery-independent surveys of trawled and un-trawled areas. Significant inroads also have been made in understanding the fate of discards as food for other organisms and effects that demersal trawling may have on habitats and consequences for macrobenthic assemblages.

Unfortunately the situation in Australia has been slow to progress to the next stage of solving the perceived problems of demersal trawl bycatch. It is clearly necessary to describe and quantify bycatches in specific fisheries (in order to assess whether any problems exist), but such work in itself is insufficient in solving the problems that arise when these bycatches are described. Once this preliminary descriptive work is done, it is necessary to test the effectiveness of alternative management strategies (such as closures and/or more selective trawl gears) which may alleviate any problems that have been detected. Several current research projects in Australia are showing the great potential that more selective trawl gears have for alleviating the chief problems concerning demersal trawl bycatch.

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Effects of an Increase in Mesh Size on the Catches of Fish Trawls off New South Wales, Australia

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Abstract. In response to claims that fish trawls off New South Wales, Australia, caught excessive quantities of under-size fish, the catches of finfish by a conventional fish trawl (constructed of 90-mm mesh in the body) were compared with those by a fish trawl constructed of 100-mm mesh in the body. Catches by the 100-mm trawl showed a 27% reduction in all by-catch and a 28% reduction in the numbers of retained tiger flathead, compared with catches by the conventional trawl. The 100-mm trawl also showed a 48% and 47% reduction in the numbers and weights respectively of discarded tiger flathead and a 57% and 63% reduction in the numbers and weights respectively of discarded rubberlip morwong. For john dory, however, at a particular locality where large numbers occurred, the 100-mm trawl caught significantly more fish than did the conventional trawl (a mean increase in weight of 66%). There is a need to determine species-specific mesh selectivities and to study the behaviour of fish in trawls. The importance of the results for the future management and operational efficiency of trawl fisheries is discussed.

Introduction

In many multi-species trawl fisheries, significant numbers of non-target organisms are caught incidentally with the target species (collectively termed 'by-catch', *sensu* Saila 1983). This by-catch often includes a large and diverse assemblage of small fish, some of which are juveniles of the target species (Kennelly 1995). The incidental capture and mortality of large numbers of these juveniles has become a source of worldwide concern in recent years because it may reduce the potential biomass and yield of recruited stocks (Gulland 1973; Howell and Langan 1987).

The increasing awareness of these problems throughout the trawl fisheries of the world has led to modifications of trawling gears and fishing practices that reduce by-catch while maintaining catches of target species (e.g. square-mesh panels and excluder devices—see Robertson and Stewart 1988; Suuronen 1990; Casey *et al.* 1992; Fonteyne and M'Rabet 1992; Walsh *et al.* 1992). Although these modifications differ in design and performance, most regulate the selectivity of trawls by incorporating minimum mesh sizes that correspond to the desired size at first capture of the target species (MacLennan 1992; Reeves *et al.* 1992). Minimum mesh sizes are key management tools in many otter-trawl fisheries because they are the most effective technique for controlling the selectivity of trawling gears (Armstrong *et al.* 1990).

Off New South Wales, Australia, the inshore otter-trawl finfish fishery extends from Crowdy Head (32°50'S, 152°45'E) to Eden (37°5'S, 149°55'E). A minimum mesh size of 90 mm was originally introduced in this fishery during the early 1950s to regulate the size at first capture of targeted tiger flathead *Neoplatycephalus richardsoni* (33 cm total length), which at the time formed the bulk of the commercial catch (Fairbridge 1952). At present in this fishery, many species are targeted throughout a wide range of depths and locations, and by-catches usually include a variety of juveniles of commercially important species. Because these species have different optimal sizes at first capture, no single mesh size would be appropriate in maximizing the catches of all species. This makes the setting of the minimum mesh size at 90 mm somewhat arbitrary because it is based only on the size at first capture of tiger flathead. Although Rowling (1979) did mesh selectivity experiments with tiger flathead, no formal trials have been done that examine the effectiveness of this and other mesh sizes in excluding under-size individuals.

Recent claims from some fishers in this fishery are that this mesh size is too small and permits the unnecessary capture and discarding of large numbers of under-size fish. This has led to the current examination of the impact on the catches of under-size and targeted individuals due to increasing mesh size in the body of the net from 90 mm to 100 mm.

Materials and Methods

This study was done in September 1993 on established fish trawling grounds off the coast of New South Wales. Two standard single-rigged otter-board fish trawl-nets made of 90-mm and 100-mm mesh were compared (Fig. 1). Both nets had the same design, rigging and taper and differed only in the size of mesh from the ground chain through to the end of the codend. These trawls were interchanged and used twice each day

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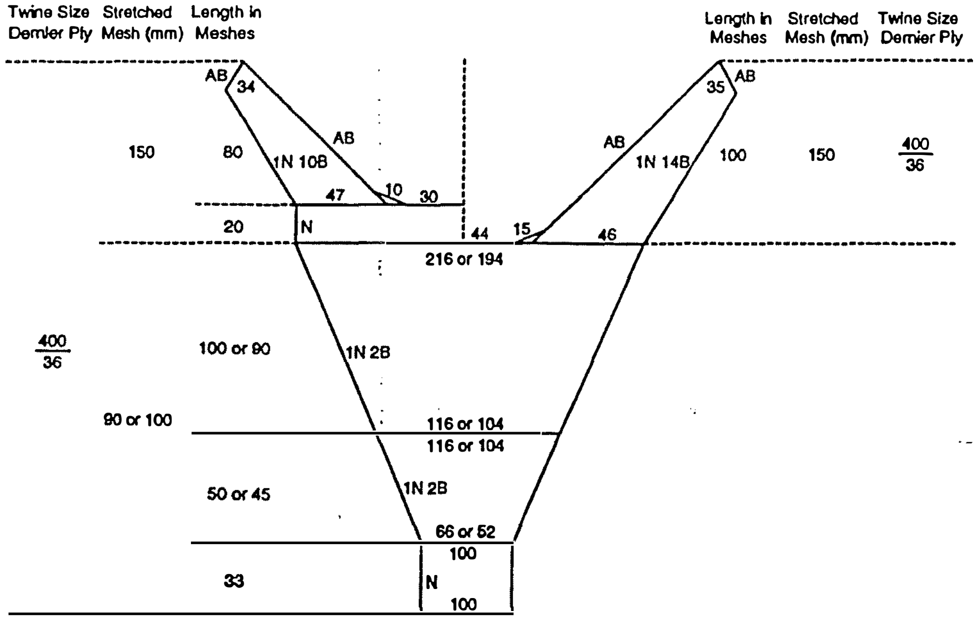

Fig. 1. Diagrammatic representation of the two nets compared in this experiment. The alternative numbers of meshes refer to the 90-mm and 100-mm nets respectively.

(between 0530 and 1530 hours) in replicate 90-min tows (approx. 3·5 kn). Three days of sampling were done at two neighbouring sites at each of two well-separated locations in the fishery: Newcastle (32°55'S, 151°46'E) in the north and Bermagui (36°25'S, 150°5'E) in the south.

After each tow, the codend was emptied onto the deck. Individuals of commercially important species that were larger than the minimum legal size (retained commercials) were separated. The remaining by-catch, including individuals of commercially important species that were smaller than the minimum legal size (discarded commercials), was then sorted. Data collected from each tow were: the weight of the total by-catch (discarded commercials and non-commercial species); the weights, numbers and sizes (to the nearest centimetre) of retained and discarded commercials; and the numbers of species in the assemblage. All individuals were counted without subsampling or estimating.

Several commercially important species were caught in sufficient quantities to allow meaningful comparisons between the two trawls. These were tiger flathead *Neoplatycephalus richardsoni*, eastern blue-spot flathead *Platycephalus caeruleopunctatus*, john dory *Zeus faber*, rubberlip morwong *Nemadactylus douglasi*, and cuttlefish *Sepia* sp.

Data for all variables were analysed by Cochran's test for homogeneity of variances, transformed if necessary, and then analysed in the appropriate four-factor analysis of variance (Underwood 1981). Locations, sites and mesh sizes were considered fixed, days were considered random, and the two random hauls per net type per day were the replicates. Sites and days were nested in locations. Those variables that occurred in only one of the locations or sites were analysed in the appropriate two- or three-factor analysis of variance. Significant differences detected in these analyses were investigated by Student–Newman–Keuls multiple comparisons of means. Where analyses of variance provided similar results for the weights and numbers of taxa, only data about weights were included in the figures to conserve space. Size frequencies of two of the most common commercial species (tiger flathead and john dory) were graphed and compared.

Results

The 100-mm net significantly reduced the weight of total by-catch (mean reduced by 27%), the numbers of retained tiger flathead (by 28%), the numbers and weights of discarded tiger flathead (by 48% and 47% respectively), and the numbers and weights of discarded rubberlip morwong (by 57% and 63% respectively) (Fig. 2 and Table 1). The 100-mm net did not significantly reduce the weights of retained tiger flathead (Table 1), but there was a mean decrease of 19% (Fig. 2). The 100-mm net did not reduce the numbers of retained commercial species or the numbers of trash species (Table 1).

There were significant interactions between sites and net type for the numbers and weights of retained eastern blue-spot flathead, john dory and cuttlefish (Fig. 3 and Table 1). The numbers and weights of retained cuttlefish and the numbers of discarded commercial species showed significant interactions between different locations and net types (Fig. 4 and Table 1). SNK tests for these data did not detect differences among means for the weights of eastern blue-spot flathead and the numbers of discarded commercial species (Figs 3*a* and 4). SNK tests did show that, at the northern Site 2, consistently more retained john dory were caught in the 100-mm net than in the 90-mm net (mean increase in weight of 66%—Fig. 3*b*) and, conversely, more retained cuttlefish were caught in the 90-mm net than in the 100-mm net (Fig. 3*c*).

Table 1. Summaries of F-ratios from analyses of variance to determine effects on variables due to different mesh sizes, days, sites and locations

The transformations used to stabilize variances (if required) are also listed. *$P < 0·05$; **$P < 0·01$; n.s., non-significant ($P > 0·05$)

Treatment	d.f.	Total by-catch	Retained tiger flathead (>33 cm)		Discarded tiger flathead (<33 cm)		Discarded rubberlip morwong (<28 cm)		Retained john dory (>20 cm)	
		(wt)	(no.)	(wt)	(no.)	(wt)	(no.)	(wt)	(no.)	(wt)
		sqrt(x+1)	sqrt(x+1)	sqrt(x+1)	ln(x+1)	ln(x+1)	ln(x+1)	ln(x+1)		
Locations (L)	1	11·29**	3·33^{ns}	4·87^{ns}	1·57**	0·01^{ns}	0·97^{ns}	1·32^{ns}	7·99*	7·40*
Sites (S)	2	1·92^{ns}	2·49^{ns}	3·55^{ns}	7·28^{ns}	4·77*	12·64**	5·27*	3·26^{ns}	2·44^{ns}
Days (D)	8	2·74*	1·67^{ns}	1·30^{ns}	0·99*	1·61^{ns}	5·09**	7·96**	12·54**	11·70*
Mesh size (M)	1	8·15*	6·63*	3·20^{ns}	15·66*	26·70**	21·36**	12·59**	2·27^{ns}	3·63^{ns}
L × M	1	0·01^{ns}	0·54^{ns}	0·56^{ns}	0·22^{ns}	0·62^{ns}	1·78^{ns}	1·26^{ns}	3·26^{ns}	3·82^{ns}
S × M	2	1·41^{ns}	1·95^{ns}	2·10^{ns}	0·08^{ns}	0·42^{ns}	0·36^{ns}	0·63^{ns}	5·25*	6·60*
D × M	8	0·55^{ns}	0·72^{ns}	0·73^{ns}	0·61^{ns}	0·48^{ns}	1·29^{ns}	1·89^{ns}	1·05^{ns}	0·82^{ns}
Res	24									

Treatment	d.f.	Retained eastern blue-spot flathead (>33 cm)		Retained cuttlefish		Discarded commercial species	Retained commercial species	Trash species
		(no.)	(wt)	(no.)	(wt)	(no.)	(no.)	(no.)
		ln(x+1)	ln(x+1)					
Locations (L)	1	0·25^{ns}	0·33^{ns}	6·65*	4·21^{ns}	0·11^{ns}	5·30^{ns}	0·93^{ns}
Sites (S)	2	4·94*	4·63*	11·65**	9·24**	0·98^{ns}	1·23^{ns}	0·39^{ns}
Days (D)	8	5·86**	4·68**	4·11*	1·82^{ns}	3·67**	4·29**	4·58**
Mesh size (M)	1	19·24**	10·64**	7·89*	3·68^{ns}	0·91^{ns}	0·11^{ns}	0·93^{ns}
L × M	1	2·10^{ns}	0·54^{ns}	8·06*	11·04*	6·68*	0·36^{ns}	2·84^{ns}
S × M	2	9·16**	4·77*	8·09*	9·29**	2·76^{ns}	0·07^{ns}	0·72^{ns}
D × M	8	0·28^{ns}	0·34^{ns}	1·06^{ns}	0·47^{ns}	0·46^{ns}	0·89^{ns}	1·50^{ns}
Res	24							

The size–frequency distributions for tiger flathead and john dory showed no differences in the ranges of sizes caught between the two nets (Figs 5*a* and 5*b*). The 100-mm net caught fewer tiger flathead than did the 90-mm net for most size classes but caught similar numbers of larger fish. Of the tiger flathead, 49% from the 90-mm net were less than legal size, compared with 40% from the 100-mm net. At the site where john dory occurred in large numbers, the 90-mm net caught fewer fish than the 100-mm net.

Discussion

This work illustrates the effects that mesh size has on the retained catch and emphasizes its importance in determining the selectivity of a trawl (Boerema 1956; Treschev 1963; Pope *et al.* 1975; Armstrong *et al.* 1990; MacLennan 1992). The results showed that increasing the size of mesh in fish trawls from 90 mm to 100 mm significantly reduced the weight of by-catch and the numbers and weights of most targeted species (e.g. tiger flathead, rubberlip morwong, cuttlefish) but increased the catch of john dory at the site where these fish occurred in large numbers (see below).

A possible reason for the decreases in catches is that the larger mesh simply permitted more fish to escape, confirming the use of minimum mesh sizes to regulate the sizes of individuals in the retained catch. However, although the 100-mm net reduced by-catches of under-size individuals by approximately 50%, it also reduced the catch of retained individuals by approximately 30%, making any increase in mesh size for this fishery to reduce by-catch quite costly in terms of landed product. For example, although the 100-mm net did not significantly reduce the weight of retained tiger flathead, the mean decrease of 19% (2·5 kg per 90-min tow) corresponds to a financial loss of approximately $6·50 per 90-min tow or $26 per day (based on the average market price for tiger flathead of $2·50 per kilogram).

The only species that did not show a decrease in catches with increasing mesh size was john dory, a key commercial and recreational species in NSW. In the site where this species occurred in large numbers, consistently more were caught in the trawl made of 100-mm mesh (Fig. 3*b*). There

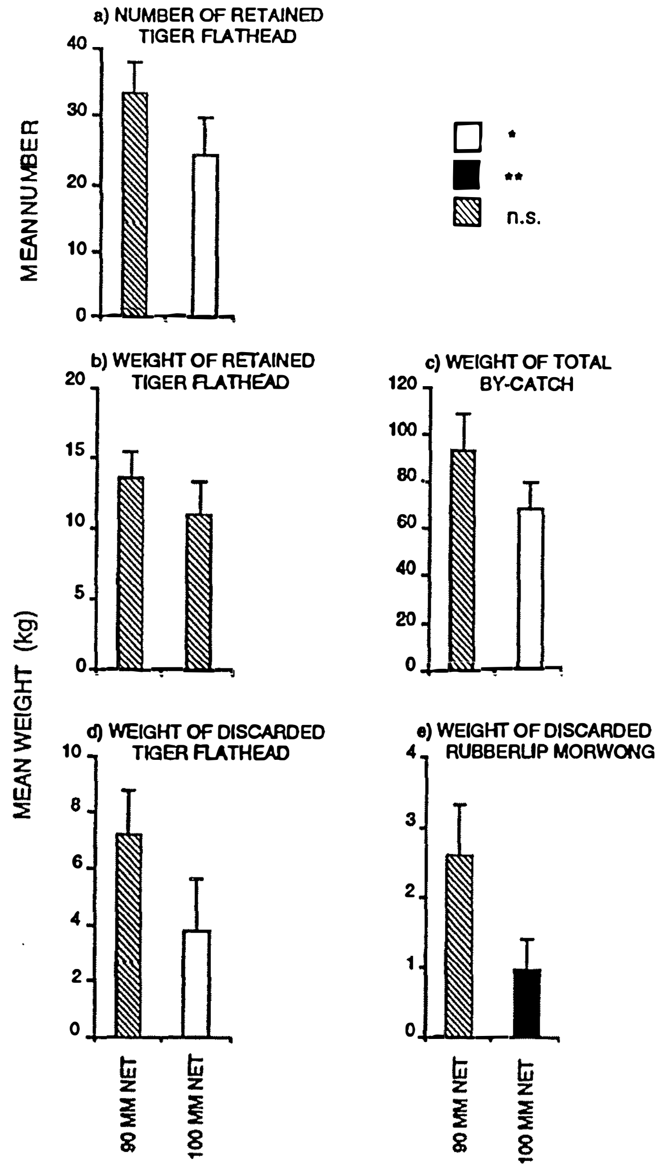

Fig. 2. Differences in mean catches ± s.e. (per 90-min tow) for *(a)* the numbers of retained tiger flathead and for the weights of *(b)* retained tiger flathead, *(c)* total by-catch, *(d)* discarded tiger flathead and *(e)* discarded rubberlip morwong ($n = 24$ for each net pooled across days). $*P < 0{\cdot}05$; $**P < 0{\cdot}01$; n.s., non-significant ($P > 0{\cdot}05$).

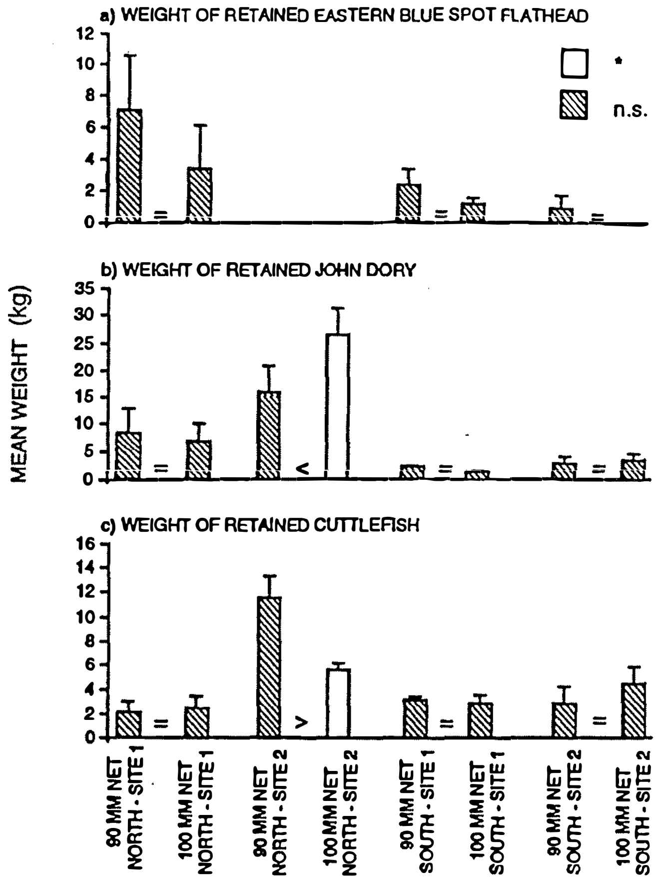

Fig. 3. Differences in mean catches ± s.e. (per 90-min tow) between sites and nets of the weights of *(a)* retained eastern blue-spot flathead, *(b)* retained john dory and *(c)* retained cuttlefish ($n = 6$ for each net pooled across days). $*P < 0{\cdot}05$; n.s., non-significant ($P > 0{\cdot}05$).

are at least two explanations for this anomaly. Firstly, because meshes in the 90-mm net have smaller openings and consequently more twine area than do those in the 100-mm net, water flow should be more restricted and so cause an increased back-pressure of water in front of the meshes (Pope *et al.* 1975; Watson 1989). Such a back-pressure may stimulate the lateral-line receptors of individuals in a crowded school and so evoke an early escape response, causing these fish to swim away from the trawl (Chapman 1964). Secondly, the reduced water flow through a 90-mm net may allow schools of john dory to maintain station inside the net during the tow and permit them to escape through the mouth of the net once the vessel is stopped and the net is hauled (Watson 1989). Obviously, these possibilities are only speculative and information on the behaviour of john dory is required to explain why more of this species (and no other) are caught in a net made of larger meshes. Nevertheless, the results from this study have obvious implications for fishers who wish to target john dory when they occur in large numbers because using larger meshes in the body of the net should decrease drag on the trawl and consequently fuel costs.

The size frequencies of one of the most common species (tiger flathead) showed that the ranges of sizes retained in both nets were similar. That is, changing the mesh size by 10 mm, although affecting the numbers and weights of fish caught, had little effect on the size range of fish caught, suggesting that these fish have a wide range of selectivity. This suggests that a minimum mesh size alone may not be

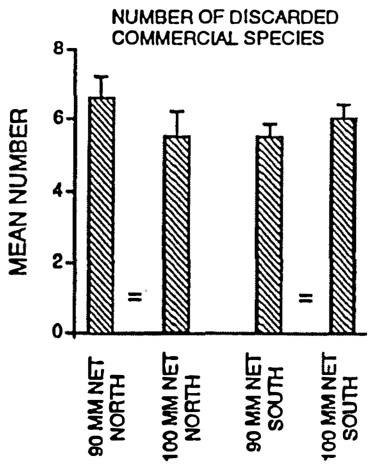

Fig. 4. Differences in mean catches ± s.e. (per 90-min tow) between locations and nets of numbers of discarded commercial species (n = 12 for each net pooled across days).

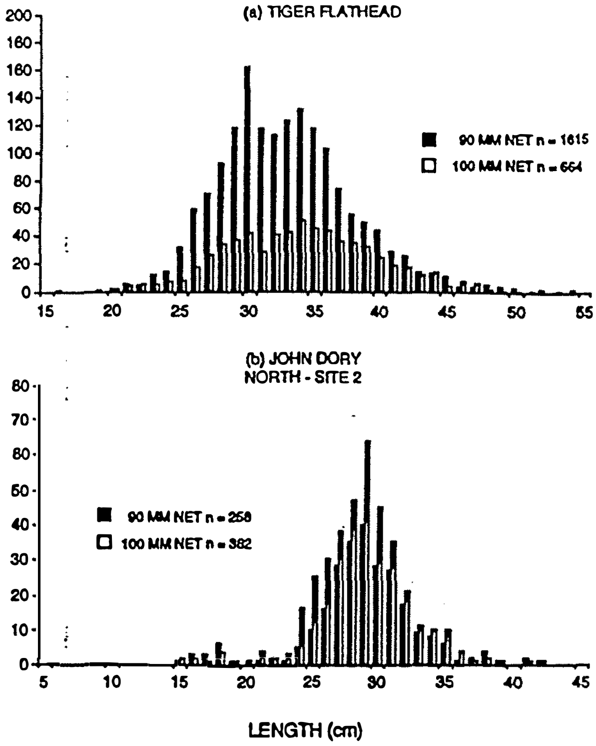

Fig. 5. Length–frequency distributions of *(a)* tiger flathead (*Neoplatycephalus richardsoni*) from each of the nets and *(b)* john dory (*Zeus faber*) from the northern site 2.

the most effective technique for excluding a maximum number of under-size individuals from the trawl.

The significant reductions in by-catch and most discarded commercials caused by increasing mesh size suggest that there is some utility in examining the effects of different sizes of mesh in the body of the trawl. However, because Wardle (1983) has shown that the wings and body of a fish trawl are primarily used as a stimulus to herd fish and that most selectivity occurs in the codend (Beverton 1963; Margetts 1963), it may be more appropriate for future selectivity experiments to concentrate on codends. Alternatively, recent successes in developing by-catch exclusion devices in trawls (e.g. Isaksen *et al.* 1992) suggest that these devices may be more appropriate in sorting under-size individuals of species that have wide ranges of selectivities (e.g. tiger flathead in the present study).

This study has demonstrated that an increase in mesh size in the body of the net from 90 mm to 100 mm has the potential to reduce the by-catch of incidental species in the NSW inshore trawl fishery, with some reductions of retained species such as tiger flathead. Conversely, an increase in mesh size seems to enhance the catch of another species (john dory). Clearly, there is a need for comprehensive selectivity experiments and behavioural observations of these species in trawls to determine the most effective trawl designs for this fishery.

Acknowledgments

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A trouser-trawl experiment to assess codends that exclude juvenile fish (mulloway) in the Hawkesbury River prawn-trawl fishery.

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Mar. Freshwater Res., 1995, 46, 953–8

A Trouser-trawl Experiment to Assess Codends that Exclude Juvenile Mulloway (*Argyrosomus hololepidotus*) in the Hawkesbury River Prawn-trawl Fishery

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Abstract. A trouser trawl was used to assess two codends designed to reduce the by-catch of juvenile mulloway in the Hawkesbury River prawn-trawl fishery. Simultaneous comparisons were made between the catches and by-catches from each codend with those from a conventional codend. The new design incorporated a panel of netting (40-mm mesh or 85-mm mesh) sewn such that the meshes were square-shaped. The panel was placed into the top of the anterior section of the codend to allow water and swimming fish to escape through these larger openings while allowing prawns to tumble along the conventional diamond-shaped netting (40-mm mesh) on the bottom of the codend (and be retained in the posterior section). Comparisons with a conventional codend (in which all meshes were diamond-shaped) showed that the codend with the 40-mm square-mesh panel reduced the by-catch of small mulloway by a mean of 44% without significantly reducing the catch of prawns. The 85-mm square-mesh panel was excluded from analysis, owing to problems associated with its construction.

Introduction

The incidental capture of non-target species (collectively termed 'by-catch') from prawn trawling is of worldwide concern (for reviews see Saila 1983; Andrew and Pepperell 1992; Alverson *et al.* 1994). Of particular interest is the by-catch and subsequent mortality of many juveniles of species that form the basis of other target fisheries (Howell and Langan 1987; Gordon 1988).

In New South Wales (NSW), Australia, estuarine trawling for school prawns, *Metapenaeus macleayi* (Haswell), occurs in five localities and is valued at approximately $A7 million per year (1990–91). A recent survey of the by-catches of the various estuarine and oceanic prawn-trawl fisheries in NSW showed that there were relatively large by-catches of juveniles of commercially and recreationally important finfishes in some of these estuaries (Kennelly 1993). In particular, the Hawkesbury River prawn-trawl fishery showed by-catches of up to approximately 300 000 juvenile mulloway, *Argyrosomus hololepidotus* (Lacépède), from late autumn to early spring each year (Kennelly 1993). Although few data are available on the population structures and dynamics of mulloway or on the extent of their post-trawl mortalities, the mere quantity of these by-catches led to concerns over potential impacts of prawn trawling on this species from commercial and recreational fishers, environmentalists, fisheries managers and scientists. The current management of this fishery is based mainly on spatial and temporal closures to trawling, but to alleviate increasing conflicts over the by-catch of this important commercial and recreational species, additional strategies have to be examined.

Several fisheries throughout the world have alleviated problems of trawl by-catch by developing gears that are more selective. In particular, square-mesh panels in codends have been used to reduce unwanted by-catch of fusiform fishes while retaining a large proportion of the intended catch. The effectiveness of square-mesh panels in codends has been quantified by *(i)* alternately towing control and modified codends on a particular fishing ground (Robertson and Stewart 1988; Casey *et al.* 1992; Fonteyne and M'Rabet 1992; Broadhurst and Kennelly 1994) or *(ii)* towing both types of codend at the same time, either by one vessel towing twin gear (Briggs 1992), by two adjacent vessels towing single gear (Thorsteinsson 1992) or by one vessel towing a net with two vertically separated codends (termed a 'trouser trawl') (Suuronen 1990; Walsh *et al.* 1992). The experimental approach used to compare different configurations is usually determined by the characteristics of the particular fishery under examination (e.g. legal gear configurations, area of trawlable ground, location, etc.) and logistics (the funding and facilities available).

In a previous experiment, Broadhurst and Kennelly (1994) used alternate hauls to compare two designs of square-mesh panels in codends with a conventional codend

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in the Hawkesbury River prawn-trawl fishery. Although this work showed promising results in reducing the by-catch of juvenile mulloway, representatives of industry expressed concern over a concomitant reduction in prawn catches, and because of variability between one tow and the next, they questioned the use of alternate hauls to compare the different designs. To make the comparisons of modified codends similar to normal commercial operations and so facilitate the acceptance of new designs by industry, a prawn net was adapted to include a trouser trawl. This permitted the direct and simultaneous comparison of a conventional codend with codends that included different square-mesh panels.

The trouser-trawl method for testing codends has been used successfully elsewhere (Nicolajsen 1988). Its relatively straightforward analysis and interpretation assumes that there are no differences in geometry between the two codends and that fish encountering the gear have an equal chance of entering the control or modified codends (see Fig. 2). There is the concern, however, that when large panels of square mesh are tested in trouser trawls, potential differences in sampling area and water flow between the two codends may result in a bias of selectivities to one side of the net (Pope *et al.* 1975). It was assumed that this did not occur in the experiment described here because the trouser trawl was designed so that the panel of square mesh was located sufficiently aft of the vertical split (3 m) and represented a negligible portion of the area of the codend. Further, both codends maintained similar geometries during the setting of the gear. Nevertheless, catches of narrow-banded sole (*Synclidopus macleayanus*), a species that cannot pass through the meshes of the codend, were compared between the two trouser-trawl 'legs' to provide an independent test of any such bias.

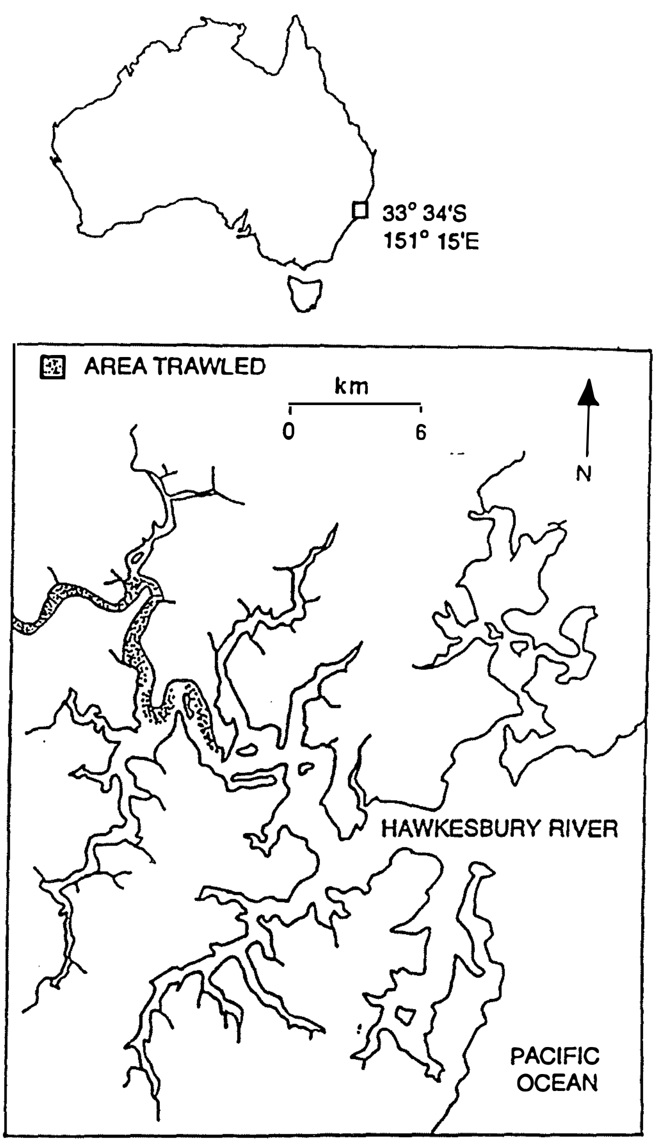

Fig. 1. Hawkesbury River and location of the area trawled.

Materials and Methods

This study, done in June 1993 on established prawn-trawl grounds in the Hawkesbury River, used a commercial prawn trawler (Fig. 1). A single locally designed prawn net (made from polyethylene and based on the Florida Flyer design) with a headline length of 11 m (mesh size 40 mm) was modified to accommodate two vertically separated sections of net, each attached to a codend. These sections were 3 m long and were attached to the body of the net at a point where the net measured 250 meshes in circumference. The sections of net were rigged so that each codend could be exchanged easily (Fig. 2). In order to represent standard commercial operations as closely as possible, this trawl was used in normal tows of between 6 and 40 min (average 25 min) at approximately 2.5 kn in depths ranging from 2 to 8 m.

The codends used in this experiment were 50 meshes long (2 m) and were constructed from 40-mm diamond-mesh netting (Fig. 3). Each codend comprised two sections: the anterior section was 25 meshes long and constructed of 2-mm-diameter twisted twine, the posterior section was 25 meshes long and constructed of 3-mm-diameter braided twine. Three designs of codend were examined. The control codend (conventionally used in this fishery) was hung so that all meshes were diamond-shaped (Fig. 3*a*). The second and third codends had a panel of netting (40-mm mesh and 85-mm mesh respectively) cut on the bar and sewn into the tops of the anterior sections of each codend (Figs 3*b* and 3*c*). We predicted that these panels would allow water and swimming fish to escape from the codends through the larger anterior openings and allow prawns to pass along the conventional diamond-shaped mesh panels on the bottom of the codend (and be retained in the posterior section).

Each codend with a square-mesh panel was compared directly with the control codend, one on each leg of the trouser trawl. The position and order of each codend was randomly determined for each tow (to eliminate any biases between different sides of the net), and each codend with a square-mesh panel was used three times per day (i.e. total of 6 tows per day). Over seven consecutive days during the trawling season, 21 replicate comparisons of each of the two treatment codends against the control were completed. To ensure that the experiment represented commercial fishing operations as closely as possible, the location and duration of each tow was selected according to the most likely location of prawns by a fisher experienced in commercial prawn trawling on the Hawkesbury River.

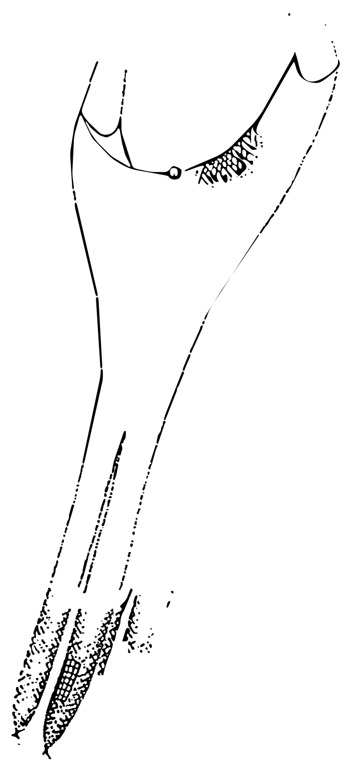

Fig. 2. Trouser-trawl configuration used to compare different codends.

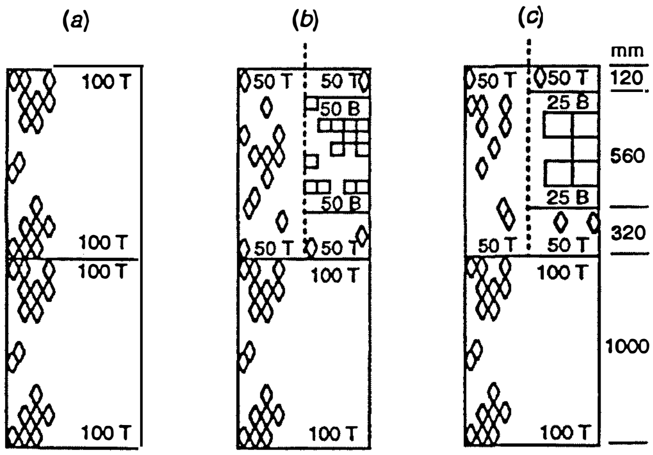

Fig. 3. Diagrammatic representation of codends used in this experiment: *(a)* control codend, *(b)* codend with the 40-mm square-mesh panel, *(c)* codend with the 85-mm square-mesh panel. T, transversals; B, bars.

After each tow, the codends were emptied separately onto the sorting tray. All organisms were sorted into different species, the most abundant being school prawns, mulloway and catfish, ***Euristhmus lepturus*** (Günther). Data recorded from each codend were: the total weight of prawns, the total weight of by-catch, the weights, numbers and sizes (to the nearest 0.5 cm) of mulloway, the weights and numbers of catfish, the numbers and sizes (to the nearest 0.5 cm) of other commercially and/or recreationally important species, the numbers of non-commercial and/or non-recreational species, and the number of species in the assemblage. All prawns in a subsample of the total prawn catch from each tow were measured in the laboratory (carapace length to the nearest millimetre).

Data for all replicates that had sufficient numbers of each variable (i.e. >10 fish or >100 g in each comparison) were analysed in one-tailed, paired t-tests. Size–frequency distributions of prawns and mulloway were plotted and compared by two-sample Kolmogorov–Smirnov tests.

One-tailed paired t-tests were done on the numbers of narrow-banded sole captured in the codend with the 40-mm square-mesh panel and the control. All individuals of this species were larger than the meshes in all codends and so provide a means to validate the symmetry of the two trouser-trawl 'legs'.

Results

The results from the codend with the 85-mm square-mesh panel were excluded from analysis because of problems associated with its rigging and performance (see Discussion).

The codend with the 40-mm square-mesh panel significantly reduced the total numbers of mulloway (mean reduction of 5.25 fish per tow, or 34%) and the numbers of mulloway less than 10 cm (mean reduction of 4.71 fish per tow, or 44%) (Figs 4*a* and 4*b*, Table 1). This codend had no

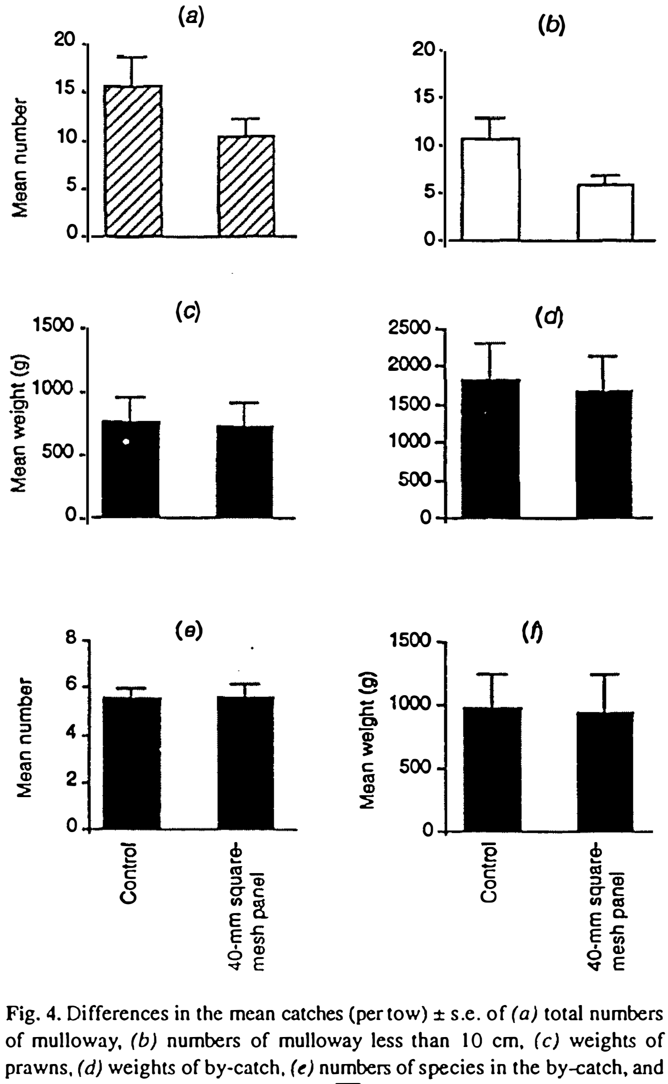

Fig. 4. Differences in the mean catches (per tow) ± s.e. of *(a)* total numbers of mulloway, *(b)* numbers of mulloway less than 10 cm, *(c)* weights of prawns, *(d)* weights of by-catch, *(e)* numbers of species in the by-catch, and *(f)* weights of catfish. Significance: ▨ $P < 0.01$; □ $P < 0.05$; ■ non-significant ($P > 0.05$).

significant effect on the weights of prawns (although the mean catch was 35.3 g, or 5%, lower), weights of by-catch, numbers of species in the by-catch, or the weights of catfish (Figs 4*c*–4*f*, Table 1). There were insufficient numbers of other commercially and/or recreationally important species caught to provide meaningful analyses.

Table 1. Summaries of one-tailed paired *t*-tests comparing different codends (control *v*. 40-mm square-mesh panel)
n, number of replicates; **significant ($P < 0.01$); *significant ($P < 0.05$)

	Paired *t*-value	*P*	*n*
Total no. of mulloway	3.187	0.004**	19
Total wt of mulloway	1.570	0.068	19
No. of mulloway <10 cm	2.405	0.026*	14
No. of mulloway >10 cm	0.961	0.178	14
Wt of prawns	1.577	0.068	15
Wt of by-catch	1.204	0.121	21
No. of species	–0.116	0.546	21
No. of catfish	1.508	0.082	16
Wt of catfish	0.339	0.37	16
No. of narrow-banded sole	1.046	0.158	13

One-tailed paired *t*-tests failed to detect significant differences in the numbers of narrow-banded sole captured in the codend with the 40-mm square-mesh panel and the control, indicating that there was no bias of selectivities to either side of the trouser trawl (Table 1).

Two-sample Kolmogorov–Smirnov tests comparing size–frequency distributions for the school prawns and mulloway measured from each sample (Figs 5*a* and 5*b*) showed no differences in the size compositions between the control codend and the codend with the 40-mm square-mesh panel ($P > 0.05$).

Discussion

The data presented here show that a codend with a square-mesh panel can selectively reduce the catch of a non-target species while maintaining the catch of the targeted prawns in the Hawkesbury River prawn-trawl fishery. In a previous experiment, Broadhurst and Kennelly (1994) examined two designs of codends with square-mesh panels and attributed the characteristics of these designs in retaining prawns and excluding mulloway to differences in the behaviours of the two species. It was suggested that fish were herded together at the taper of the codend, which upset the balance of the school and initiated an escape response

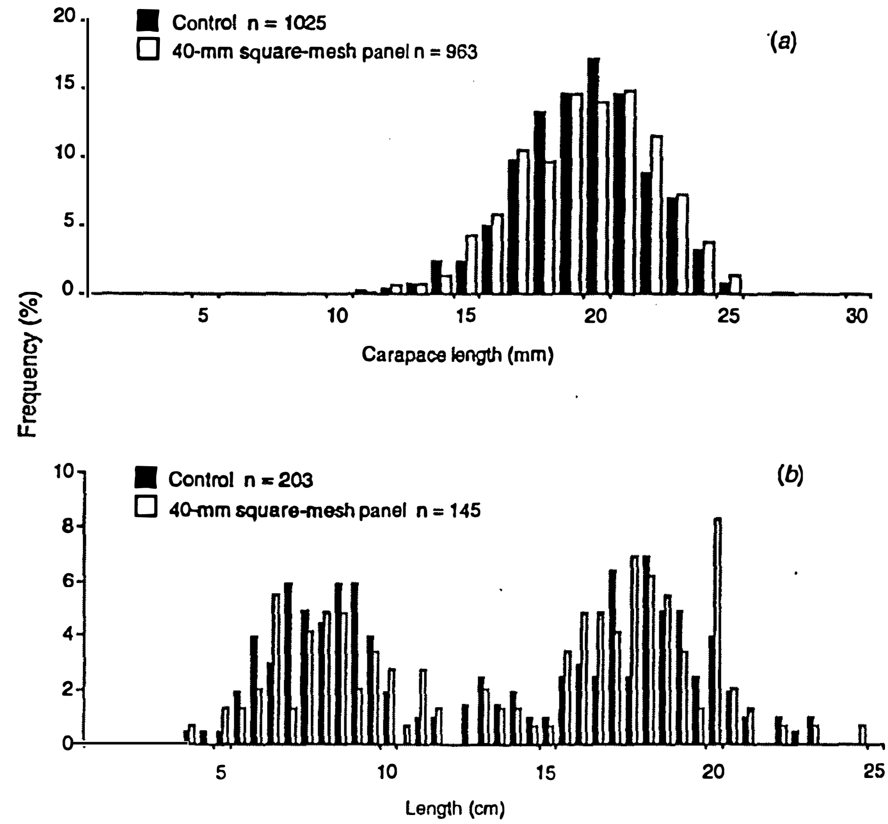

Fig. 5. Length–frequency distributions of *(a)* school prawns (*Metapenaeus macleayi*) and *(b)* mulloway (*Argyrosomus hololepidotus*) from the control codend and the codend with the 40-mm square-mesh panel.

towards the sides and top of the net. If the meshes were open in this area, then the school passed through (see also Briggs 1992). This behaviour may have been enhanced by differences in hydrodynamic pressure at the front of the posterior section of the codend (caused by greater twine area and closed meshes in the posterior section). In contrast, benthic invertebrates such as prawns seemed to display a limited response to such stimuli (perhaps owing to physiological differences) and were forced against the meshes, eventually tumbling down the net. Once in the rear of the codend, their retention depended on mesh size rather than on any active escape response (Lochhead 1961; Main and Sangster 1985; Newland and Chapman 1989).

The two codends with square-mesh panels examined in the present paper were designed to take advantage of the theory discussed above by incorporating a square-mesh panel on the top of the anterior section of the codend only, so that small fish (mulloway) might still escape with fewer losses of prawns. The results suggested that this occurred in the codend with the 40-mm square-mesh panel: there was no significant reduction in the weights of prawns, but there was a 34% reduction in the total numbers of mulloway and a 44% reduction in the numbers of mulloway less than 10 cm (Figs 4*a*–4*c*, Table 1).

The results from the codend with the 85-mm square-mesh panel were excluded from analysis because of problems associated with its performance. These were attributed to the installation of the square-mesh panel and the associated changes in the geometry of the whole codend, since it is difficult to attach 85-mm mesh to 40-mm mesh and still maintain an even symmetry of meshes. Further, this square-mesh panel may have become convoluted owing to the attachment of 25 bars of 85-mm mesh to 50 meshes of 40-mm mesh. Robertson (1986) suggests that to calculate the number of square meshes required to achieve maximum openings, it is necessary to determine the fractional mesh opening of the diamond mesh to obtain an estimate of the fishing circumference. Application of this procedure to both experimental codends shows that approximately 12 bars of 85-mm mesh and 25 bars of 40-mm mesh should have been attached to 50 meshes of 40-mm mesh. This might have resulted in a greater exclusion of mulloway from the codend with the 40-mm square-mesh panel and in a positive result from the codend with the 85-mm square-mesh panel.

Kolmogorov–Smirnov tests failed to detect any differences between the size compositions of prawns and mulloway captured in the codends analysed (Figs 5*a* and 5*b*), but there were proportionally fewer mulloway under 10 cm retained in the codend with the 40-mm square-mesh panel (Fig. 4*b*; see above). The exclusion of these small mulloway is a particularly important result in terms of alternative management strategies because larger, faster-swimming fish have a greater chance of avoiding prawn trawls altogether.

The results suggested that there is potential for the development of a codend with square-mesh panels that excludes a large proportion of mulloway while retaining acceptable quantities of prawns. One possible modification to the codends described in the present paper would be to increase the amount of netting around the anterior section of the codend to about 150 meshes. This should increase the hydrodynamic pressure towards the square openings and further assist the escape of free-swimming fish (Broadhurst and Kennelly 1994).

Although the effectiveness of codends with square-mesh panels is apparent (see also Broadhurst and Kennelly 1994), there remains a question of the extent of post-trawl mortalities associated with the escape of fish (Main and Sangster 1988; DeAlteris and Castro 1992). For example, fish may lose scales and damage fins and gills during movement through square meshes, contributing to overall stress and possibly resulting in some mortality (Briggs 1992). Although results from other studies suggest that these effects may be minimal (Main and Sangster 1988; DeAlteris and Reifsteck, in press), future research into modified trawl gears should include an assessment of this question.

Results of the present study suggest that a trouser-trawl configuration can be used to assess a codend with a square-mesh panel in a fishery restricted to the use of single trawl gear. The advantage of this technique is that it removes any confounding effects due to spatial and temporal heterogeneity that could occur in experiments involving alternate hauls. This is particularly important in prawn-trawl fisheries that use single gear on trawl grounds where catches of prawns and by-catch can vary greatly from one tow to the next.

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The by-catch issue and the effects of trawling.

Kennelly, S.J., 1996.

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Chapter 32. The by-catch issue and the effects of trawling[1]

International concern about the effects of oceanic drift nets on cetaceans, turtles, billfish and other pelagic species resulted in widespread banning of the practice. Increasing concerns are now held about the effects of otter-board demersal fish and prawn trawling. The 'by-catch', or that part of the catch which is captured incidentally to the target species, often comprises the bulk of the trawler's catch. In Australia virtually all of the so-called 'trash' is thrown overboard. For example, in 1988 the by-catch from the Northern Trawl Fishery was estimated to be 47,000 tonnes (mostly fish), 97% of which was discarded at sea.

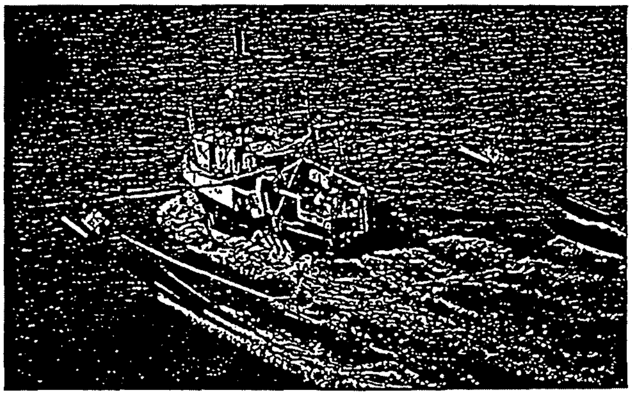
The by-catch issue is not a recent problem in Australia. In 1880 a Royal Commission identified problems of prawn netting in New South Wales, and in 1904 H.C. Dannevig, an early fisheries scientist, investigated the prawn by-catch problem in Sydney Harbour. However, the by-catch from most of our fisheries still remains undescribed, effects on fisheries and the environment are poorly known, and there have been few attempts to address the problem via closures or modified fishing gear.

Although fishing gear such as fish traps, crab pots, longlines, droplines, rods and reels are designed to be selective in what they catch, there is almost always some incidental catch. Gear such as gillnets and otter trawls are less selective, and have the potential of taking a large quantity and wide diversity of other species.

Studies of the effects of trawling

The by-catch of the Northern Prawn Fishery in the Gulf of Carpentaria has been investigated by CSIRO and Northern Territory Fisheries over the past decade to assess its potential commercial usage and the effects of trawling on turtle populations. Around 4,000 turtles were found to be netted each year, of which around 250 died by drowning. While this was not considered a major danger to these populations of turtles by the researchers, others consider it so (Chapter 18).

The by-catch of oceanic and estuarine prawn trawl fisheries has been investigated by New South Wales Fisheries following claims of large-scale mortality of juvenile fish. Hundreds of thousands of juvenile snapper, bream and mulloway were found to be taken each year but impacts on stocks were difficult to assess because mortalities from trawling, natural mortalities, and biomasses of stocks, are not well known. Using the best information available, the by-catch of juvenile snappers in Botany Bay was estimated to be around 350,000 fish per year, representing a possible decline of about 60,000 legal-size fish three years later.



(Source: GBRMPA)

Figure 32.1: There are concerns in many parts of Australia about the effects of trawling on the sea floor.

One of the best attempts to quantify effects of trawling was done by CSIRO in the fish trawl fishery on the North West Shelf. Comparisons were made of surveys done before and after commercial fishing began, and in areas closed and open to fishing. Effects on benthos were also assessed using underwater video. It was found that trawl fishing reduced snapper populations (the target of a trap fishery), increased populations of less valuable species such as threadfin bream and lizard fish, and reduced abundances of benthic organisms.

In the Gulf of Carpentaria, CSIRO compared surveys undertaken prior to the establishment of commercial trawling with those undertaken after 20 years of fishing. Significant decreases were found in 18 taxa, and in the overall diversity of assemblages. Another study in the Gulf found that by-catch of fish in Albatross Bay was less than 10% of the total stock

[1] Based on a paper by Dr S. J. Kennelly, New South Wales Fisheries, Cronulla, New South Wales

(around 93,000 tonnes). A large number of fish species were found to be affected by prawn beam trawling in Moreton Bay (Qld) but few significant effects were found in a study of the Hawkesbury River (NSW) prawn fishery.

Effects on food webs

Trawling may have subtle, indirect effects on species assemblages by the removal of large epibenthic organisms and by the alteration of food webs. The death of the by-catch organisms may affect populations of their predators and prey, competitors and other species.

The survival rate of discarded by-catch is quite small. In experiments in Torres Strait and Moreton Bay, around 70% of crustaceans survived a week after capture, but fish survival was very low with only one species recording a survival rate over 30%. Around half the discarded fish floated, while most crustaceans sank. The floating discards were eaten by birds, sharks and dolphins, and sinking discards were eaten by sharks. Dead discards reaching the bottom were eaten by other fish, sharks and crabs. In Moreton Bay the sand crab fishery may benefit from the discarded prawn by-catch, and three major species of seabirds feed primarily on these discards.

Utilisation of by-catch

A major objection by the non-trawl fisheries and the general public is the waste of discards. In many fisheries the by-catch is retained for separate sale or for fish meal. Use of by-catch is minimal in Australia because of limited storage space on trawlers, small market demand, low prices and problems with including toxic species in fish meals. Slipper lobsters, trawl whiting, squids and octopus are by-catch of the Eastern King Prawn Fishery that have a growing domestic market. Specimen shells, sea snakes (for fashion leather) and seahorses and pipefish (for Chinese medicines) are also in demand in Queensland. A study of the by-catch of the Northern Prawn Fishery found that only a few by-catch species such as slipper lobsters, snappers, emperors, large mackerel and cods were retained. Some 43 other species of fish, sharks, crustaceans and molluscs, with an estimated annual landing of 15,300 tonnes, were discarded.

(Source: B. Russell, NT Museum, GBRMPA)

Figure 32.2: Asian trawlers on the North West Shelf (WA) removed large areas of sponges and other benthos

Management alternatives

While Australians are gaining some awareness of the issues and problems of trawl by-catch, there has been little research on ways of minimising effects.

Trawl closures one alternative

CSIRO research on the North West Shelf demonstrated the effectiveness of closures. Extensive areas of the Great Barrier Reef Marine Park are closed to trawling (all zones except General Use 'A'), including a large cross-shelf transect in the Far Northern Section. Closures are unpopular with fishers where valuable fisheries exist, and violations have been frequent. Fisheries managers are concerned that increasing fishing effort is redirected toward areas open to trawling, causing increased damage. Considerable research will be necessary to identify if, where and when closures can be implemented without affecting the economic viability of the fishery.

(Source: GBRMPA)

Figure 32.3: By-catch from the Northern Prawn Fishery. There are some concerns about turtle mortalities.

More selective gear another alternative

Research on the development and implementation of more selective gear and fishing practices to minimise the by-catch and mortality of unwanted organisms is in its infancy in Australia compared to other countries. For example, 'Turtle Excluder Devices' (TEDs) and other by-catch excluders are commonly used in the United States.

A modified semi-demersal fish trawl (the 'Julie Anne'), trialled in the Northern Prawn fishery took 43% of the by-catch and 3% of the epibenthos of a conventional trawl. An American net (the 'Morrison soft TED') trialled in the New South Wales King Prawn fishery [illegible] by-catch by excluding all [illegible] collection sock at the end of the net) larger than the mesh size of the TED panel. Modifications involving square-mesh panels have been developed in New South Wales and these allow swimming juvenile fish to escape before reaching the cod end .

A variety of modifications of fish and prawn trawls were described in the 1992 International Conference on By-Catch in the Shrimp Industry and at the American Fisheries Society's meeting in 1993. Many are demonstrated to be effective but require modification to suit local fisheries and conditions. The close involvement of the Australian fishing industry in such gear development is considered essential.

Summary and conclusions

1. The by-catch resulting from trawl fisheries is one of the central issues in fisheries and marine environmental management in Australia.

2. Insufficient information is known of the by-catch of most Australian fisheries.

3. Possible effects include reduction in juveniles of targeted and other species, adult fish and invertebrates; removal of epibenthos; and changes to food webs, including increase in populations of scavengers such as seabirds, fish and crabs.

4. Management options include development of by-catch products and markets, development of more selective fishing gear, and spatial and temporal closures to trawling.

5. The involvement of the industry in all aspects of the research and management of this issue is essential.

6. Despite some studies of impacts of trawling, Australia has lagged in by-catch utilisation and particularly in the development of more selective gear.

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Effects of square-mesh panels in codends and of haulback-delay on bycatch reduction in the oceanic prawn-trawl fishery of New South Wales, Australia.

Broadhurst, M.K., S.J. Kennelly and G. O'Doherty, 1996.

Fishery Bulletin, Vol. 94, pp. 412-422.

Abstract.–Two experiments were conducted in the New South Wales oceanic prawn-trawl fishery, 1) by comparing catch from a conventional codend with that from two new codend designs with square-mesh panels and 2) by showing the effects on catches of a short delay in haulback of trawls with square-mesh panels. The two new codend designs incorporated panels of netting (85-mm mesh) sewn such that the meshes were square-shaped (measuring 7 × 11 bars) and inserted lengthwise and widthwise into the tops of the anterior sections. Simultaneous comparisons among these designs and a conventional codend showed that both designs performed similarly by significantly reducing the weights of bycatch that would be discarded (by 46% and 38%, respectively) without significantly reducing the catch of the prawn *Penaeus plebejus*. The second experiment showed that juvenile red spot whiting, *Sillago flindersi*, an important commercial finfish, escaped from the square-mesh panels in the trawl during a 10–15 second haulback delay. Trawls without any haulback delay showed no significant reduction in the bycatch of this species. The results are discussed in terms of the probable behavior of fish in the modified trawls and in terms of the implications that factors such as haulback delay may have on the survival of fish escaping through square-mesh panels in codends.

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Effects of square-mesh panels in codends and of haulback delay on bycatch reduction in the oceanic prawn-trawl fishery of New South Wales, Australia

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In many of the world's prawn-trawl fisheries, significant numbers of nontarget organisms (collectively termed "bycatch," sensu Saila, 1983) are caught incidentally with targeted prawns. This bycatch often includes a large and diverse assemblage of small fish, some of which are juveniles of commercially and recreationally important species (for reviews see Saila, 1983; Andrew and Pepperell, 1992; Alverson et al., 1994; Kennelly, 1995). The incidental capture and mortality of large numbers of these juveniles has been of worldwide concern in recent years because it may reduce the potential biomass and yield of stocks that form the basis of other fisheries (Gordon, 1988; Foldren, 1989).

In New South Wales (NSW), Australia, oceanic prawn trawling involves approximately 300 vessels that usually operate during the night from 11 ports. This fishery is valued at approximately A$17 million per annum and primarily targets the eastern king prawn, *Penaeus plebejus*, although a significant proportion of the total income is derived from the sale of legally retained bycatch (termed "byproduct"), which comprises several commercially important species of fish, crustaceans, and cephalopods (see Kennelly et al., 1992). However, a recent survey examining the spatial and temporal distributions and abundances of the catch and bycatch from four ports in this fishery showed that juveniles of commercially important species comprised a significant portion of the bycatch (Kennelly[1]). Athough many of these juveniles showed large temporal and spatial variabilitiy in their occurrence, some (e.g. red spot whiting, *Sillago flindersi*, and eastern blue spot flathead, *Platycephalus caeruleopunctatus*), were consistently caught in large numbers throughout the sampling period. Although there are few data available on the population structure and dynamics of the key bycatch species or on the extent of their post-trawl mortalities, the quantities involved have raised concerns regarding potential detrimental impacts of prawn trawling on future stocks of these species (Kennelly, 1993). We therefore began an investigation that examined various modifications to trawling gear and trawling practices that minimize undesirable bycatch while maintaining catches of prawns and commercial byproduct.

[1] Kennelly, S. J. 1993. Study of the bycatch of the NSW east coast trawl fishery. Final report to the Fisheries Research and Development Corporation, P.O. Box 222, Deakin, ACT, 2600, Australia. Project No. 88/108. ISBN 0 7310 2096 0, 520 p.

One suite of modifications to trawls that has been successful throughout the world in reducing bycatches while retaining the target catch involves the use of square-mesh panels in codends (Robertson and Stewart, 1988; Carr, 1989; Briggs, 1992; Broadhurst and Kennelly, 1994; Robertson[2]; Isaksen and Valdemarsen[3]; Suuronen[4]). Quantifying the effectiveness of square-mesh panels in codends has been approached by a variety of experimental methods. At the simplest level, catches and bycatches from control and modified codends have been compared by using alternate tows (Robertson and Stewart, 1988; Broadhurst and Kennelly, 1994), by towing both codends as twin gear (Briggs, 1992), by using trouser trawls (Walsh et al., 1992; Suuronen[4]), or by towing either gear from two adjacent vessels (Thorsteinsson, 1992). Alternatively, covers of small-mesh netting over modified codends have provided estimates of the quantities of fish escaping (Robertson and Stewart, 1988).

Although these kinds of experiments have determined the effectiveness of square-mesh panels in codends, without direct observations by divers or cameras there is no information available on the patterns of behavior of escaping fish or on the period when escapement occurs during tows. The latter point raises an important issue with respect to the survival rates of escaped catch. Because fish are exhausted to varying degrees owing to the stress associated with capture (see Wardle, 1983; Main and Sangster[5]), the ultimate efficiency of square-mesh panels in reducing bycatch mortality is determined by the rate at which nontarget individuals are excluded. The survival of these individuals is probably inversely proportional to the time spent in the trawl, because studies have shown that fish that remain in the codend are subjected to high levels of stress and fatigue (Main and Sangster[5]; Main and Sangster[6]).

Observations from divers, from video cameras, and from towed submersibles, have provided conflicting information on the behavior of escaping fish (Wardle, 1983, 1989; Watson, 1989; Briggs, 1992; Watson et al., 1993). For example, in the Irish Sea, Briggs (1992) observed that the escape of European whiting, *Merlangius merlangus,* occurred continually throughout the duration of the tow. In contrast, Watson et al's (1993) studies in the Gulf of Mexico showed that red snapper, *Lutjanus campechanus,* maintained their position within the codend throughout the tow and escaped only when haulback was initiated.

In the NSW oceanic prawn-trawl fishery there is commonly a delay of up to 15 seconds (s) between slowing the vessel and engaging the winch to haul in the trawl (termed haulback delay). Because of this delay, possible effects, such as those observed by Watson et al. (1993), need to be investigated prior to interpreting the effectiveness of square-mesh panels in codends. Direct observations of such effects, however, always assume that the divers or cameras have no artificial effects on the behavior of the fish or on the normal commercial operation of the gear. While it may be reasonable to assume minimal effects in conditions with adequate light, Wardle (1989) found that the use of cameras with artificial light at night or in turbid conditions (below 10^{-3} lux) disorientated fish and disturbed their behavior. The possibility of such effects makes this technique unsuitable for assessing the effects of haulback delay on square-mesh panels in the NSW oceanic prawn-trawl fishery which operates at night.

Our specific goals in this experiment were 1) to investigate the effectiveness of square-mesh panels in reducing the bycatch from the NSW oceanic prawn-trawl fishery and 2) via a manipulative experiment, to provide an accurate and inexpensive means to determine the effects of haulback delay on the performance of these designs.

Materials and methods

Two experiments were conducted on commercial prawn-trawl grounds east of Yamba, New South Wales (29°26'S, 153°22'E), between August and October 1994 by using a commercial prawn trawler (13.8 m). Three florida flyers (mesh size 42 mm), each with a headline length of 12.8 m, were rigged in a standard triple gear configuration (see Andrew et al., 1991, for details) and towed at 2.5 knots. Each of the identical outside nets were rigged with zippers (no. 10 nylon open-ended auto lock plastic slides) to facilitate changing of the codends (see Broadhurst et al., in press). Because the middle net was not rigged

[2] Robertson, J. H. B. 1983. Square mesh cod-end selectivity experiments on whiting (*Merlangius merlangus* (L.)) and haddock (*Melanogrammus aeglefinus* (L.)). Int. Counc. Explor. Sea, council meeting 1983/B:25, 13 p. [Mimeo.]

[3] Isaksen, B., and J. W. Valdemarsen. 1986. Selectivity experiments with square mesh codends in bottom trawl. Int. Coun. Explor. Sea, council meeting 1986/B:28, 18 p. [Mimeo.]

[4] Suuronen, P. 1990. Preliminary trials with a square mesh codend in herring trawls. Int. Counc. Explor. Sea, council meeting 1990/B:28, 14 p. [Mimeo.]

[5] Main, J., and G. I. Sangster. 1988. Scale damage and survival of young gadoid fish escaping from the cod-end of a demersal trawl. *In* J. DeAlteris (ed.), Proceedings of selectivity and survivability workshop, p. 17–34. Univ. Rhode Island Sea Grant Advisory Service, Narragansett, RI.

[6] Main, J., and G. I. Sangster. 1991. A study of haddock (*Merlanogrammus aeglefinus* (L.)) behavior in diamond and square-mesh codends. Scot. Fish. Work. Paper 19/91, 25 p.

exactly like the outside nets (see Andrew et al., 1991), it was excluded from our analyses.

The codends used in the experiments measured 75 meshes long (3 m) and were constructed from 40-mm mesh netting (Fig. 1). They comprised two panels. The anterior panel was 100 meshes in circumference and constructed of 25 meshes of 48-ply twine attached to 25 meshes of 35-ply twine. The posterior panel was 200 meshes in circumference and constructed of 3-mm diameter braided twine.

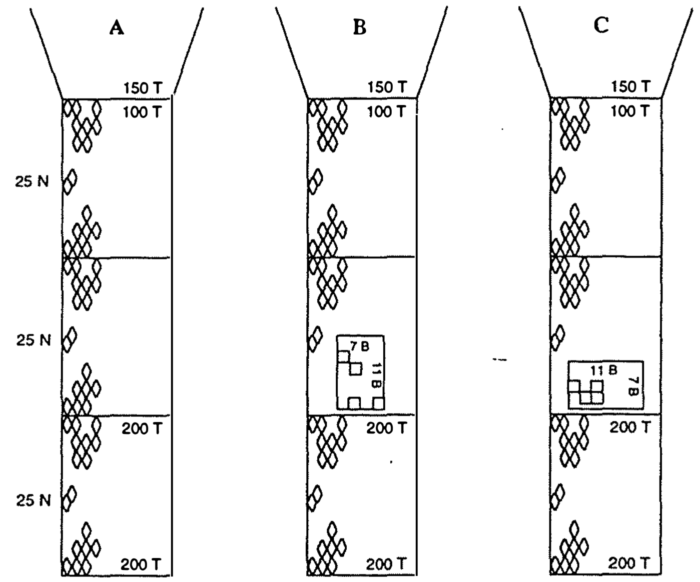

Figure 1

Diagrammatic representation of (A) the control codend, (B) the 85-mm-long codend and (C) the 85-mm-wide codend (T=transversals; B=bars; N=normals).

Experiment 1—evaluation of codends

Three codend designs were compared. The control codend was made entirely of diamond-shaped meshes (Fig. 1A). The second codend (termed the 85-mm-long codend) had a panel of 85-mm netting cut on the bar (7 bars × 11 bars) inserted lengthwise into the top of the anterior section (Fig. 1B). The third codend (termed the 85-mm-wide codend) had the same panel inserted sideways into the top of the anterior section (Fig. 1C).

All three codends were compared against each other in independant, paired trials. That is, in separate tows, the 85-mm-long codend was compared against the control; the 85-mm-wide codend was compared against the control; and the 85-mm-long and 85-mm-wide codends were compared against each other. The particular pair to be compared in a given tow were placed on each outside net of the triple-rigged gear. The position and order of each codend was determined randomly (to eliminate any biases between different nets) and the codends were used in normal commercial tows of 90-min duration (with a haulback delay of 10–15 s) on established prawn-trawl grounds. Over six nights we completed a total of 10 replicate tows of each paired comparison. Prior to the trials and at the end of each night, we rigged the outside nets with normal commercial codends and performed tows to ensure that there were no differences in the fishing characteristics of each net.

Experiment 2—effects of haulback delay

In this experiment the 85-mm-long codend from experiment 1 was tested against the control for possible effects due to haulback delay. The codends were interchanged between tows, and each night we completed two replicate 90-min tows that included 1) a 10–15 s haulback delay (measured as the duration between slowing the vessel and engaging the winch) and 2) no haulback delay. Over 4 nights we completed a total of 8 replicate tows for each type of haulback. To ensure independence among tows, the location and direction of each tow was randomly selected from the available locations on established grounds northeast of Yamba. The grounds trawled varied in depth and ranged between 20 and 25 fm.

Data collected from the experiments

After each tow in each experiment, the codends were emptied onto a partitioned tray. Prawns and all commercially important species larger than the minimum legal size (retained commercials) were separated from the remaining bycatch. The remaining bycatch (termed discarded bycatch) was then sorted. This included individuals of commercially important species that were smaller than the minimum legal size (discarded commercials). Data collected from each tow were the total weight of prawns and their size (to the nearest 1-mm carapace length); the weight of the discarded bycatch; the weights, numbers, and sizes (to the nearest 0.5 cm) of discarded commercial species and retained commercial species; and the numbers of noncommercial species in the assemblage. All individuals were counted without subsampling. Several commercially important species were caught in sufficient quantities to allow meaningful comparisons. These were eastern king prawn, *Penaeus plebejus*, cuttlefish, *Sepia* sp., Octopus, *Octopus* sp., red spot whiting, *Sillago flindersi*, eastern blue spot flathead, *Platycephalus caeruleopunctatus*, and smooth bug, *Ibacus* sp.

The paired comparisons done in experiment 1 were analyzed with one-tailed, paired *t*-tests. Data from experiment 2 were analyzed with two-factor analysis of variance (Underwood, 1981) after testing for homogeneity of variances (Cochran's test). Further, treating the data from each haulback-delay period separately, we compared data from the pairing of the 85-mm-long and control codends, using one-tailed, paired *t*-tests. Data from the 85-mm-long codend and its control (which used the haulback delay of 10–15 s in experiment 2) were combined with data from these codends in experiment 1, to provide a larger dataset for analysis of the results for the 85-mm-long codend. Size frequencies of prawns and red spot whiting from both experiments and the combined data were compared by using two-sample Kolmogorov-Smirnov tests (P=0.05).

Results

Experiment 1—evaluation of codends

Both the 85-mm-long and 85-mm-wide codends significantly reduced the weight of discarded bycatch (means reduced by 46% and 38%, respectively) (Fig. 2A; Table 1). The 85-mm-wide codend significantly reduced the number and weight of discarded red spot whiting (by 71% and 75%), and the number of trash species (Fig. 2, D–F; Table 1). There were insufficient data from the 85-mm-long codend to analyze data for red spot whiting (<2 fish per replicate). Neither of the codends with square-mesh panels significantly reduced the catch of prawns (Table 1), although the mean catches were 7.5% lower in the 85 mm long codend and 2.5% lower in the 85-mm-wide codend (Fig. 2G). Apart from a significant reduction in the number of trash species with the use of the 85-mm-long codend (Fig. 2F; Table 1), there were no other detectable differences between the two codends with square-mesh panels. Two-sample Kolmogorov-Smirnov tests comparing the size-frequency distributions for the king prawns and red spot whiting measured from each sample showed no significant differences in the relative size compositions between any of the codends tested.

Experiment 2—effects of haulback delay

There were no significant effects due to haulback delay on the differences in catch between the control and 85-mm-long codends for the weight of bycatch and prawns (Fig. 3, A–B; Table 2). However, haulback delay significantly increased the difference in catch between the control and 85-mm-long codends for the number and weight of red spot whiting and decreased the weight of retained cuttlefish (Fig. 3, C–E; Table 2). There were no significant effects among any of the other variables (i.e. retained octopus, discarded eastern blue-spot flathead, smooth bug, and trash species) due to haulback delay. The number and weight of red spot whiting were significantly differ-

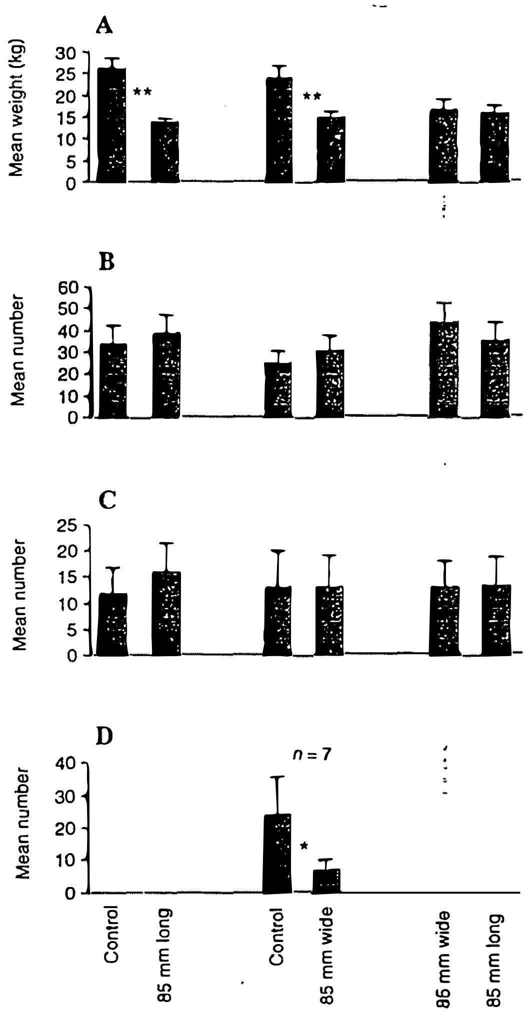

Figure 2

Differences in mean catch (±SE) between each of the codends in experiment 1 (evaluation of codends): (**A**) the weight of discarded bycatch; (**B**) the numbers of retained octopus (*Octopus* sp.); (**C**) the numbers of discarded cuttlefish (*Sepia* sp.); (**D**) the number of discarded red spot whiting (*Sillago flindersi*); (**E**) the weight of discarded red spot whiting (*Sillago flindersi*); (**F**) the number of noncommercial species; and (**G**) the weight of prawns (*Penaeus plebejus*). * = P<0.05; ** = P<0.01; unless stated otherwise, n = 10.

ent among nights in the experiment. No variables displayed significant interactions among haulback delay and nights (Table 2).

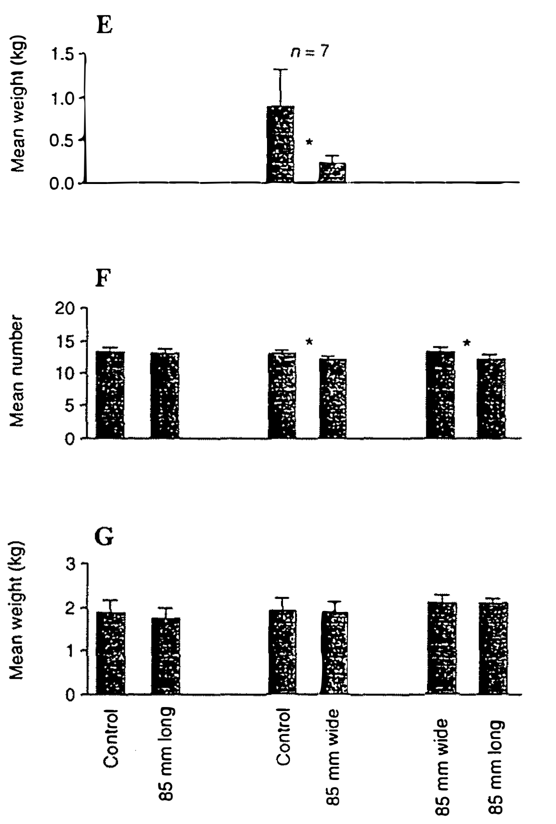

Figure 2 (continued)

One tailed, paired t-tests comparing data from the control and 85-mm-long codends showed that the 85-mm-long codend significantly reduced the weight of bycatch and significantly increased the weight of prawns during both a 10–15 s delay and no delay in haulback (Fig. 3, A–B; Table 3). The 85-mm-long codend significantly reduced the number and weight of discarded red spot whiting compared with the control during the 10 to 15 s haulback delay (means reduced by 64% and 56%, respectively) (Fig. 3, D–C; Table 3). There was no significant reduction in these variables for this codend when there was no delay in haulback, although the mean numbers and weights of red spot whiting were reduced by 21% and 25%, respectively (Fig. 3, D–C; Table 3). The weight of retained cuttlefish was significantly decreased in the 85-mm-long codend when there was no delay in haulback (Fig. 3E; Table 3). No other variables showed any differences between the control and 85-mm-long codends either with or without a delay in haulback. Two-sample Kolmogorov-Smirnov tests comparing size-frequency distributions for king prawn and red spot whiting (Fig. 4) measured from each sample showed no significant differences in the relative size compositions between the 85-mm-long and control codends during either a 10–15 s delay or no delay in haulback.

Aggregated data for the 85-mm-long codend

Combining all the data for the 85-mm-long codend, we found that this modification significantly reduced

Table 1

Summary of one-tailed paired t-tests comparing number and weight of catch of three different codends. n = number of replicates; rsw = red spot whiting.

	Control vs. 85-mm-long			Control vs. 85-mm-wide			85-mm-long vs. 85-mm-wide		
	Paired t-value	P	n	Paired t-value	P	n	Paired t-value	P	n
Weight of prawns	1.458	0.089	10	−0.357	0.635	10	0.000	—	10
Weight of discarded bycatch	6.355	0.0001**	10	5.800	0.0002**	10	0.491	0.317	10
Number of discarded cuttlefish	−2.17	0.971	10	0.638	0.269	9	−0.066	0.526	10
Weight of discarded cuttlefish	−0.656	0.736	10	−0.219	0.584	9	−0.264	0.601	10
Number of retained cuttlefish	0.810	0.219	10	0.819	0.217	10	−1.213	0.871	10
Weight of retained cuttlefish	1.331	0.108	10	−0.599	0.718	10	−0.077	0.530	10
Number of retained octopus	−1.847	0.952	10	−2.202	0.973	10	1.451	0.090	10
Weight of retained octopus	−0.248	0.595	10	−0.972	0.822	10	0.346	0.368	10
Number of discarded rsw	(insufficient data)			2.242	0.033*	7	(insufficient data)		
Weight of discarded rsw	(<2 fish per replicate)			2.223	0.034*	7	(<2 fish per replicate)		
Number of noncommercial sp.	1.246	0.122	10	2.228	0.026*	10	2.283	0.024*	10

*P=<0.05; **P=<0.01.

the weight of bycatch (mean reduction of 37%) and the number and weight of red spot whiting (by 68% and 58%, respectively) (Figs. 5, A–C; Table 4). This codend did not significantly reduce the weight of prawns (although the mean catch was 3% lower) nor any of the other variables (Fig. 5E; Table 4). Two-sample Kolmogorov-Smirnov tests failed to detect any significant difference in the size compositions of prawns between the 85-mm-long and control codends (Fig. 6A). The sizefrequency distributions for red spot whiting, however, were significantly different between these codends (Fig. 6B).

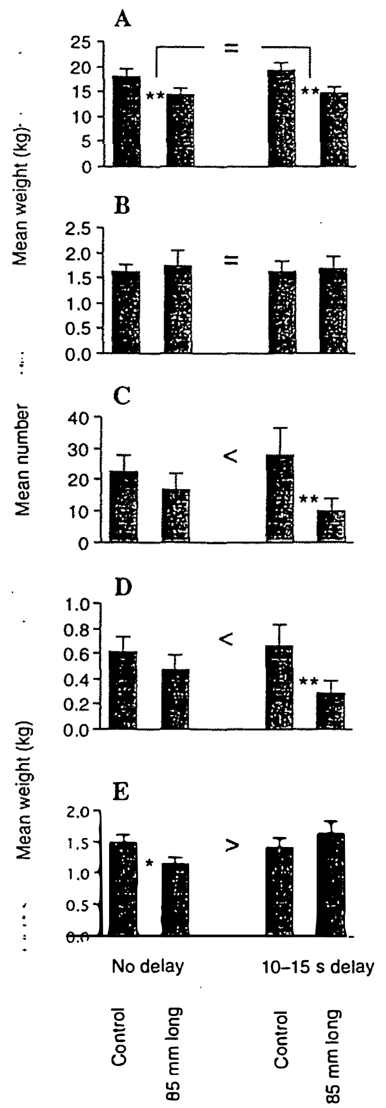

Figure 3

Differences in mean catch (±SE) between the control and 85-mm-long codends in experiment 2 (effects of haulback delay) for no delay and a 10–15 s delay in haulback (<, >, and = indicate direction of differences): (**A**) the weight of discarded bycatch; (**B**) the weight of prawns (*Penaeus plebejus*); (**C**) the number of discarded red spot whiting (*Sillago flindersi*); (**D**) the weight of discarded red spot whiting (*Sillago flindersi*); and (**E**) the weight of retained cuttlefish (*Sepia* sp.). * = $P<0.05$; ** = $P<0.01$.

Discussion

The results of these experiments show that codends with square-mesh panels have the potential to reduce bycatch of nontarget individuals (see also Robertson and Stewart, 1988; Briggs, 1992; Fonteyne and M'Rabet, 1992; Broadhurst and Kennelly, 1994). By experimentally examining the effects of haulback delay, we have also quantified, for the first time, the effects that such operational procedures can have on the escape of some individuals.

In previous experiments, Broadhurst and Kennelly (1994, 1995) showed that square-mesh panels in the anterior sections of codends were effective in releasing small fish (i.e. mulloway, *Argyrosomus hololepidotus*) from prawn trawls in the Hawkesbury River. These results were attributed to the differences in behavior of fish and prawns in their response to

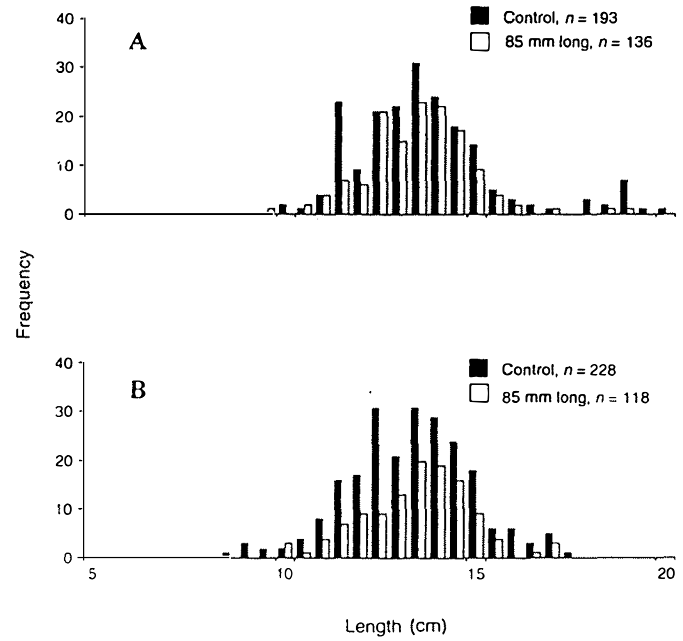

Figure 4

Length-frequency distributions of red spot whiting (*Sillago flindersi*) from the control and 85-mm-long codends for experiment 2: (**A**) during no delay in haulback and (**B**) a 10–15 s delay in haulback.

Table 2

Summary of F-ratios from two-way analyses of variance to determine effects on variables (weight and number of catch) due to haulback delay on different nights.

Treatment	df	Prawns (wt.)	Discarded bycatch (wt.)	Retained octopus (no.)	Retained octopus (wt.)	Retained cuttlefish (no.)	Retained cuttlefish (wt.)	Discarded eastern blue spot flathead (no.)	Discarded eastern blue spot flathead (wt.)	Discarded red spot whiting (no.)	Discarded red spot whiting (wt.)	Discarded smooth bugs (no.)	Discarded smooth bugs (wt.)	Trash species (no.)
Haulback delay (HD)	1	0.25	0.93	0.02	0.01	4.86	9.24*	0.13	0.06	8.25*	7.48*	0.26	2.77	0.02
Nights (N)	3	1.83	1.07	0.12	0.03	0.60	0.91	0.28	0.74	6.13*	5.95*	3.74	0.66	0.57
HD × N	3	2.51	2.26	0.21	1.13	1.78	0.60	0.44	0.96	0.156	0.58	1.07	0.48	1.30
Residual	8													

*P<0.05.

Table 3

Summary of one-tailed paired t-tests for the effect of haulback delay on weight and number of catch for control and 85-mm-long codends. n = 8 for all comparisons; rsw = red spot whiting; ebs = eastern blue spot flathead.

	No haulback delay		10–15 second haulback delay	
	Paired t-value	P	Paired t-value	P
Weight of prawns	0.903	0.198	−0.595	0.715
Weight of discarded bycatch	7.976	0.0001**	4.610	0.001**
Number of retained octopus	−0.242	0.592	−0.043	0.516
Weight of retained octopus	1.560	0.081	0.979	0.180
Number of retained cuttlefish	1.964	0.045*	−1.085	0.844
Weight of retained cuttlefish	2.694	0.015*	−1.843	0.946
Number of discarded ebs	−0.403	0.951	−0.989	0.823
Weight of discarded ebs	−0.956	0.815	−0.712	0.751
Number of discarded rsw	1.072	0.159	3.464	0.0005**
Weight of discarded rsw	0.778	0.231	3.984	0.002**
Number of discarded smooth bugs	−0.037	0.639	−0.716	0.752
Weight of discarded smooth bugs	−0.333	0.626	−0.477	0.676
Number of noncommercial sp.	0.477	0.334	0.174	0.433

*P<0.05; **P<0.01.

stimuli from the trawl and to the hanging configurations of the codends. Fish were apparently herded together at the taper of the codend, invoking an escape response to the sides and top of the net. The attachment of an anterior panel of 100-mesh circumference to a posterior panel constructed of heavy twine and 200-mesh circumference, presumably created a back pressure of water that was directed out through the open anterior square meshes, facilitating the escape of fish. This sequence of events was assumed to occur continually throughout the duration of the trawl. The response of prawns to this stimuli appeared fairly limited; other studies have shown that prawns are not capable of maintaining active escape responses to the trawl and are quickly forced against the meshes and towards the back of the codend (Lochhead, 1961; Main and Sangster, 1985; Newland and Chapman, 1989).

The two square-mesh codends used in experiment 1 were designed to take advantage of the theory discussed above by incorporating a panel of square mesh on top of the anterior section only, so that small fish might escape without a reduction in the catch of prawns or of larger commercially important bycatch

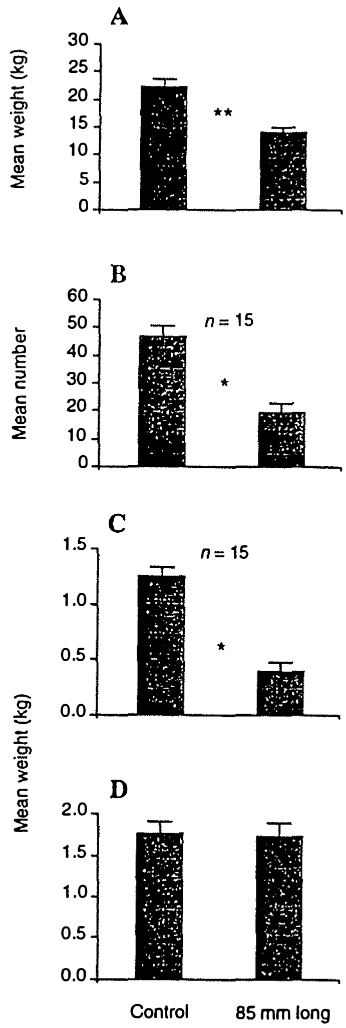

Figure 5

Differences in mean catch (± SE) between the control and 85-mm-long codend, combined across both experiments: (**A**) the weight of discarded bycatch; (**B**) the number of discarded red spot whiting, *Sillago flindersi;* (**C**) the weight of discarded red spot whiting, *Sillago flindersi;* and (**D**) the weight of prawns *Penaeus plebejus*. * = $P<0.05$; ** = $P<0.01$; unless stated otherwise n = 18.

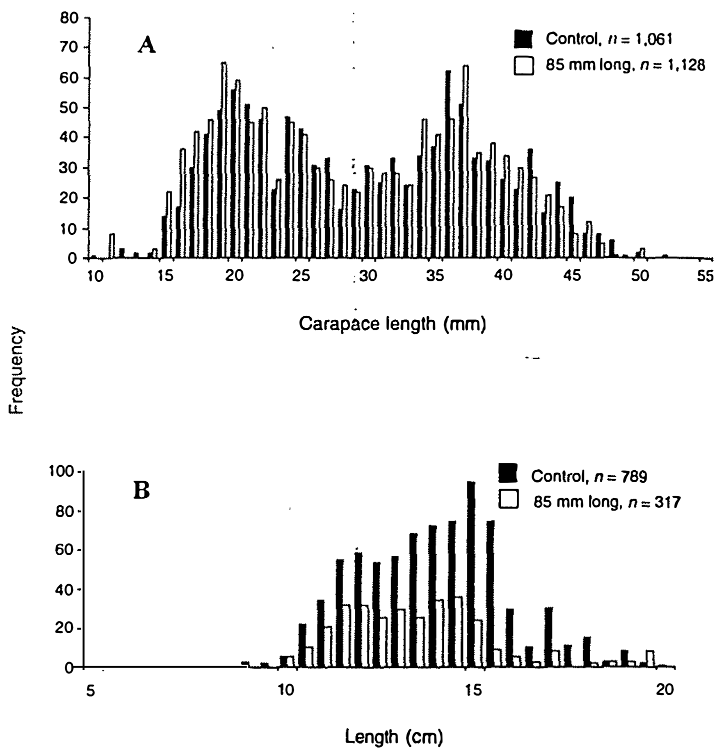

Figure 6

Length-frequency distributions of (**A**) king prawn, *Penaeus plebejus*, and (**B**) red spot whiting, *Sillago flindersi*, from the control and 85-mm-long codends combined across experiments.

species. Both the 85-mm-wide and 85-mm-long codends performed similarly, significantly reducing the weight of discarded bycatch (by 48% and 38% respectively) with no significant reduction in the weight of prawns or retained species (Fig. 2; Table 1). The 85-mm-wide codend also significantly reduced the number and weight of red spot whiting by 71% and 75%, respectively (Fig. 2; Table 1), whereas, based on the aggregated data, the 85-mm-long codend reduced these by 68% and 58%, respectively (Fig. 5; Table 4).

Experiment 2 compared the differences between the control and 85-mm-long codends with and without a short (10–15 s) delay during haulback. The results suggest that the individuals comprising discarded bycatch escaped continually throughout the duration of the tow (Fig. 3A; Table 2). Their behavior and escape from the square-mesh panel may be explained, therefore, according to the theory discussed above. For red spot whiting, however, there was no significant reduction in number or weight when there was no delay in haulback (although the means were reduced by 21% and 28%, respectively), but there was a significant reduction of 64% and 56.6%, respectively, for the tows that included a 10–15 s delay (see Figs. 3 and 6; Table 3). Red spot whiting, therefore, did not appear to exhibit the same behavior as the other species because the majority of these fish appeared to escape during the 10–15 s delay in haulback.

Table 4

Summary of one-tailed, paired *t*-tests comparing control and 85-mm-long codends trialed with a 10–15 s haulback delay, combined over both experiments. *n* = number of replicates; rsw = red spot whiting.

	Control vs. 85-mm-long		
	Paired *t*-value	*P*	*n*
Weight of prawns	1.000	0.165	18
Weight of discarded bycatch	5.720	0.0001**	18
Number of retained cuttlefish	0.355	0.363	18
Weight of retained cuttlefish	0.566	0.289	18
Number of retained octopus	–0.948	0.822	18
Weight of retained octopus	–0.169	0.566	18
Number of discarded rsw	1.935	0.036*	15
Weight of discarded rsw	2.185	0.023*	15
Number of noncommercial sp.	1.587	0.065	18

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

A possible reason why few red spot whiting escaped continuously during trawling is that there were insufficient stimuli generated in the codend to invoke an escape response. This hypothesis is supported by previous studies that have shown that physiological and behavioral differences between species are major factors in the effectiveness of escape panels (Robertson and Stewart, 1988; Briggs, 1992; Fonteyne and M'Rabet, 1992). The subsequent escape of red spot whiting from the 85-mm-long codend during the 10–15 s haulback delay may have been a result of additional stimuli generated by changes in the geometry of the codend. For example, Watson (1989) observed that during haulback, differences in the contours of the codend and associated water flow caused fish to aggregate and become disorientated. The fish then increased their swimming speeds and randomly charged the meshes around the codend. By opening the meshes in this area (i.e. by our inclusion of the 85-mm-long square-mesh panel), we may have stimulated some fish to escape the trawl.

The delayed escape of red spot whiting from the 85-mm-long codend raises important questions concerning the extent of their mortality during trawling and after escape. Because previous studies have shown that fish that remain in the codend experience greater stress and fatigue than those that escape continuously, those individuals escaping at the end of the tow may suffer greater mortality. Further, such post-trawl mortality, particularly among smaller fish, may increase in proportion to tow duration. Obviously such effects on red spot whiting should be investigated prior to commercial use of the 85-mm-long codend per se, because, unless most of the escaping fish survive, such designs are of little value.

It may be possible to reduce the problems of trawl mortality for red spot whiting by altering the design of the 85-mm-long codend so that more fish escape continuously during trawling. One possible modification to the design would be to make the square-mesh panel longer (see Briggs, 1992), allowing more red spot whiting to escape at random along the codend. This may also provide juveniles of other commercially important species (i.e. cuttlefish, octopus, and eastern blue spot flathead) the opportunity to escape, although there was little evidence in our experiments to suggest that these species displayed active escape response toward the square-mesh panel (see Figs. 2 and 3; Tables 1–3). Their lack of exclusion is more likely attributable to intraspecific variability in behavioral responses rather than to the design of the square-mesh panel (see also Robertson and Stewart, 1988; Briggs, 1992).

Another modification to allow more red spot whiting to escape the trawl continuously may be to increase the size of mesh used in the panels. However, the size-frequency composition of red spot whiting captured in the 85-mm-long codend and control showed that the size of mesh used in the panel allowed fish within the range of sizes sampled to escape, including some individuals of commercial size (>16 cm) (Fig. 4). Further, this size of mesh resulted in no significant reduction in the weight of prawns, nor were there any significant differences detected in the size composition of prawns between the control and the 85-mm-long or 85-mm-wide codends. Subsequent increases in the size of mesh may, therefore, result in further loss of commercial red spot whiting and possibly some reduction in the catch of prawns.

The square-mesh codends tested in these experiments provide further evidence of the effectiveness of this type of exclusion device in reducing the bycatch of unwanted species, while maintaining the catch of prawns and other species of commercial size. Further, for a fishery that retains a range of species, these designs offer a relatively simple and inexpensive method for eliminating a large part of the incidental catch. It is evident from the results, however, that not all species to be excluded behave in a similar manner and that the effects of operational procedures such as haulback delay can significantly influence the rate of exclusion of some species. Therefore, it is imperative that future research into exclusion designs, such as square-mesh panels, include an assessment of such operational factors so that the full impact of bycatch excluders on reducing the mortality of incidentally caught juveniles can be assessed.

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Assessments of modified codends that reduce the by-catch of fish in two estuarine prawn-trawl fisheries in New South Wales, Australia

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Abstract

Four experiments, comparing catches and by-catches from a conventional codend with several modified codends, were done in two estuarine prawn-trawl fisheries in New South Wales, Australia. The modified codends were designed to reduce by-catch and included panels of square-mesh, soft mesh separating panels and a Nordmøre-grid. Compared to a conventional codend, the codends with square-mesh panels showed no significant differences in catches of school prawns (*Metapenaeus macleayi*) nor by-catches. The codends with soft mesh separating panels showed different results between locations. In the Clarence River estuary, these designs significantly reduced by-catch (up to 70%) with no reduction in catches of school prawns, while similar designs tested in Botany Bay showed significant reductions in by-catches and catches of king prawns (*Penaeus plebejus*) (up to 58% and 34% respectively). In the Clarence River the codend with the Nordmøre-grid, showed a significant reduction in by-catch (77%) with no reduction in catches of school prawns compared to a conventional codend. The results are discussed in terms of the probable behaviour of fish and prawns in the modified trawls, the need for fishery-specific designs of by-catch reducing trawl modifications and the implications of introducing such designs into normal commercial practice.

Keywords: Modified codends; By-catch reduction; Prawn-trawls; Selectivity

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1. Introduction

The incidental capture of non-target species, collectively termed 'by-catch' (sensu Saila, 1983), from prawn trawling has attracted world-wide attention over the past few years. For reviews see Saila (1983), Andrew and Pepperell (1992) and Alverson et al. (1994). Of particular concern is the mortality of large numbers of juveniles of commercially and recreationally important species, since this is thought to reduce the recruitment, biomass and yield of stocks that form the basis of other fisheries (Gordon, 1988; Foldren, 1989; Cooper, 1990). Increased awareness of these problems will mean that this issue will remain one of the most important challenges facing commercial and recreational fisheries throughout the world (Tillman, 1993).

In New South Wales, Australia, estuarine prawn trawling occurs in five locations and is valued at approximately A$7 $\times 10^6$ per annum (1990–91). Over the past 10 years the by-catch from these fisheries has become of increasing concern to a broad cross section of the community, particularly commercial and recreational fishers, conservationists, fisheries managers and scientists. Primarily, these concerns are directed towards prawn trawlers catching and discarding large numbers of under-size fish that, when larger, are targeted in other commercial and recreational fisheries.

This increasing conflict resulted in a 3 year observer-based study which quantified the distributions and abundances of by-catch species throughout the N.S.W.'s prawn-trawl fisheries (Kennelly et al., 1992). The information collected revealed relatively large by-catches of juveniles of commercially and recreationally important finfishes in most of these fisheries. While many by-caught species showed large temporal and spatial variabilities, some were caught in large numbers throughout entire trawling seasons. In particular, the Clarence River prawn-trawl fishery showed large by-catches of juvenile bream (*Acanthopagrus australis*), tailor (*Pomatomus saltatrix*) and sand whiting (*Sillago ciliata*) (Liggins and Kennelly, 1996), and Botany Bay showed large by-catches of several important species, especially juvenile snapper (*Pagrus auratus*) (Liggins et al., unpublished). Although there is little data available on the population structure and dynamics of these species, nor estimates of their post-trawl mortalities, the quantities of by-catch have led to concerns over the potential impacts of prawn trawling on these species. An investigation was initiated, therefore, which examined possible methods of minimising undesirable by-catch in N.S.W.'s estuarine prawn trawl fisheries.

Recent studies on excluding by-catch from prawn-trawl gear have concentrated on modifying the codend to incorporate trash exclusion devices (TEDs). At their simplest level, these devices may be categorized according to the methods used to promote by-catch escape: (i) those which exploit behavioural differences between prawns and finfish (Wardle, 1983; Wardle, 1989; Main and Sangster, 1985; Watson, 1989) using strategically placed escape 'windows' (Watson et al., 1986; Matsuoka and Kan, 1991; Rulifson et al., 1992) or panels of square-mesh in codends (Isaksen and Valdemarsen, 1986; Briggs, 1992; Thorsteinsson, 1992; Broadhurst and Kennelly, 1994) and (ii) those that mechanically partition the catch using some form of separating panel within or immediately anterior to the codend (Kendall, 1990; Isaksen et al., 1992). This panel may be made of netting that has larger meshes than the targeted prawns, (Christian and

Harrington, 1987; Kendall, 1990) or may be constructed using a solid grid, e.g. the Nordmøre-grid (Isaksen et al., 1992).

The type of modification used in codends to reduce by-catch depends on the individual characteristics of the fishery under examination (e.g. the size of nets, methods of handling, location of trawl grounds), the species to be excluded and the extent to which the behaviour of the target and by-catch species are understood (Watson, 1989). For example, Broadhurst and Kennelly (1994); Broadhurst and Kennelly (1995) showed that square-mesh panels in codends were effective in excluding large quantities of small fusiform fish, without significant loss of prawns. This type of exclusion device was easy to install and had no adverse effect on the setting and retrieval of the gear, an important consideration for the small-scale operations typical of estuarine trawling. Although solid and/or complex separator TEDs are not generally favoured by fishers, studies have shown that the application of these is essential in some fisheries which seek to exclude large individuals (Isaksen et al., 1992). Such devices need to be carefully designed so they do not affect normal fishing methods (i.e. setting and retrieval of gear) nor interfere with the geometry of the trawl.

In seeking to develop the most suitable by-catch reducing modifications to trawl gears for particular fisheries, it is therefore necessary to have information on species–specific spatial and temporal variabilities in by-catches and a sound understanding of the commercial techniques employed. Further, it is important to appreciate that, because of the large variabilities inherent in the magnitudes and compositions of by-catches across fisheries, it is unlikely that one design will be suitable over a range of fisheries and locations (Rulifson et al., 1992). The application of particular solutions must be specific to individual fisheries and based on a sound understanding of the species to be excluded and retained (Averill, 1989).

Our specific goals in this paper were to complete a series of experiments under normal commercial fishing conditions to determine the prawn-retention and by-catch exclusion characteristics of several modified codends. To facilitate acceptance of these designs by fishers, representatives of industry were involved in all aspects of this research and particularly in the design and construction of gears and the execution of field trials.

2. Materials and methods

Three experiments were done in the Clarence River and one in Botany Bay between December 1993 and March 1994 (Fig. 1), using commercial prawn trawlers (both 10 m) on established trawl grounds. All trawls were 'Florida Flyers' (mesh size 40 mm) rigged so that the codends could be exchanged and connected to wooden otterboards with upper and lower bridles.

The codends used in the experiments were constructed from 40 mm mesh netting and measured 50 meshes in length (2 m). They comprised two panels: the anterior panel was 25 meshes long and constructed of 2 mm diameter twisted twine; the posterior panel was 25 meshes long and constructed of 3 mm diameter braided twine.

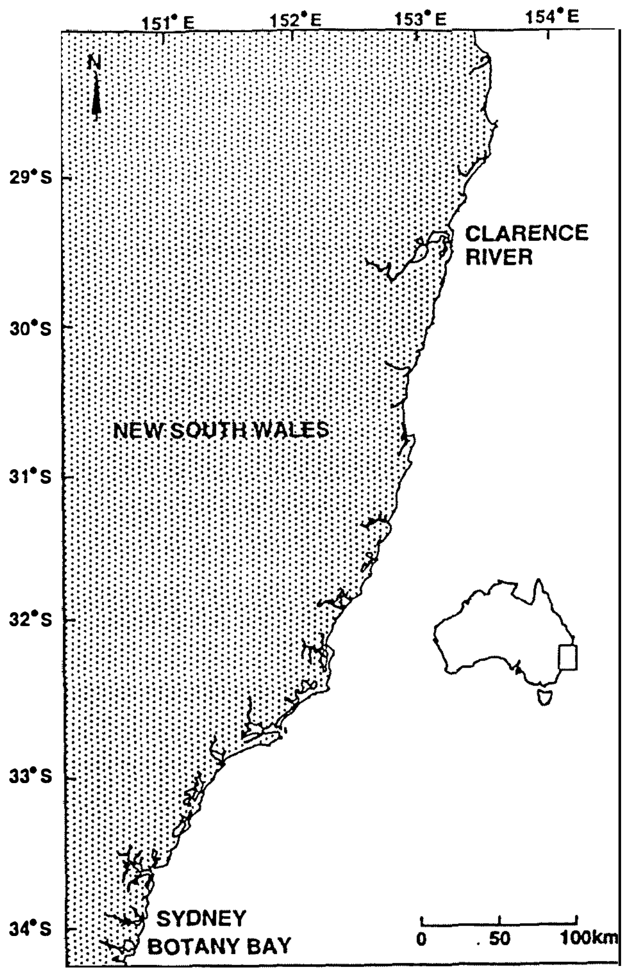

Fig. 1. The coast of New South Wales and locations of the estuaries in which the experiments were done.

Because of different regulations governing the fishing operations in these estuaries, the Clarence River experiments were done using a twin rig system (each with a headline length of 7.32 m), whilst the Botany Bay experiment was done using a single net (with a headline length of 10.97 m). These nets were towed at a ground speed of approximately 2.5 knots in depths ranging from 2 to 5 m. Because the results of each experiment affected the design of subsequent experiments, we provide details of each experiment in chronological order.

2.1. Clarence River Experiment 1

Five codend designs were examined. The control codend (Codend 1), conventionally used in the Clarence River fishery, was made entirely of diamond-shaped meshes (Fig. 2(A)). Codends 2 and 3 had panels of large diamond-shaped netting (150 mm mesh and 203 mm mesh respectively) inserted into the tops of the anterior sections (305 mm x 305 mm), close to the leading edge of the posterior section (Fig. 2(B)). Codends 4 and 5 were similar to Codends 2 and 3, but included rigid aluminium frames around the

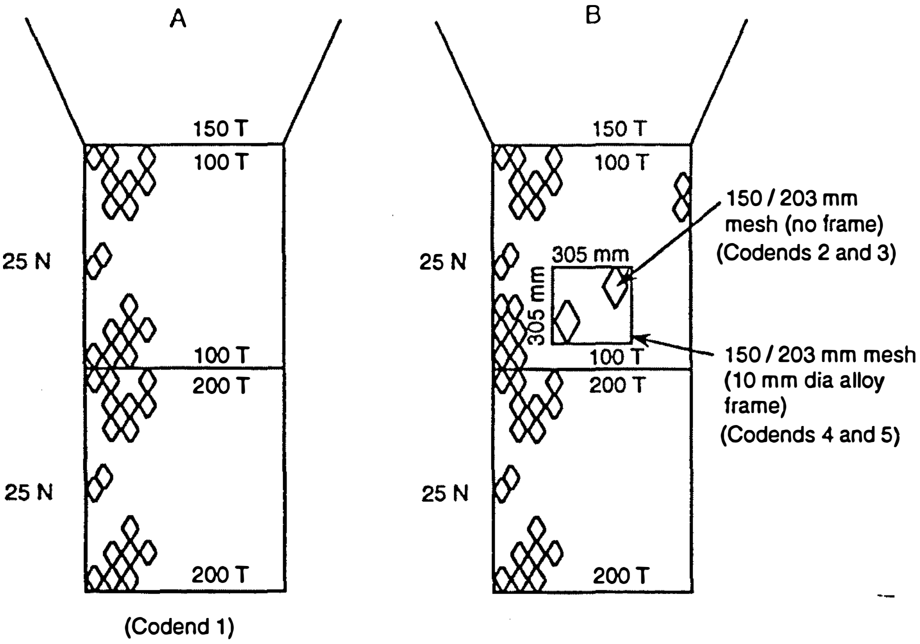

Fig. 2. Diagramatic representation of codends tested in Clarence River Experiment 1: (A) control codend and (B) modified codends (where T,transversals; B, Bars and N, normals).

perimeter of the large mesh panels. These frames were inserted to facilitate the removal of windows of different sizes of mesh and to ensure that meshes were kept open.

Each modified codend was directly compared to the control codend, one on each net of the twin rigged gear. The position and order of each codend was randomly determined and each modified codend was used twice per day in normal commercial tows of between 8 and 61 min duration. Over 5 days during the trawling season, we completed a total of ten replicate comparisons of each treatment codend against the control.

2.2. Clarence River Experiment 2

The codends used in the second experiment in the Clarence River were constructed using the same materials and configurations as those described above, but incorporated modifications to the anterior sections. In this experiment, three modified codends were tested against a control codend. The first and second modified codends had panels of netting (150 mm mesh and 203 mm mesh) cut on the bar and inserted into the tops of the anterior sections (Fig. 3(A)). These panels were slightly larger (305 mm x 457 mm) than those described in Experiment 1 and were located at the top leading edge of the anterior sections. The third modified codend, termed the 90 mm separator panel codend (SPC) had a separating panel (constructed of 90 mm mesh) attached at the bottom of the leading edge of the anterior section (hanging ratio of 90%) and sewn along the bars terminating at an escape window (305 mm x 457 mm and constructed of 203 mm square-mesh) at the top leading edge of the posterior section (hanging ratio of 50%) (Fig. 3(B)).

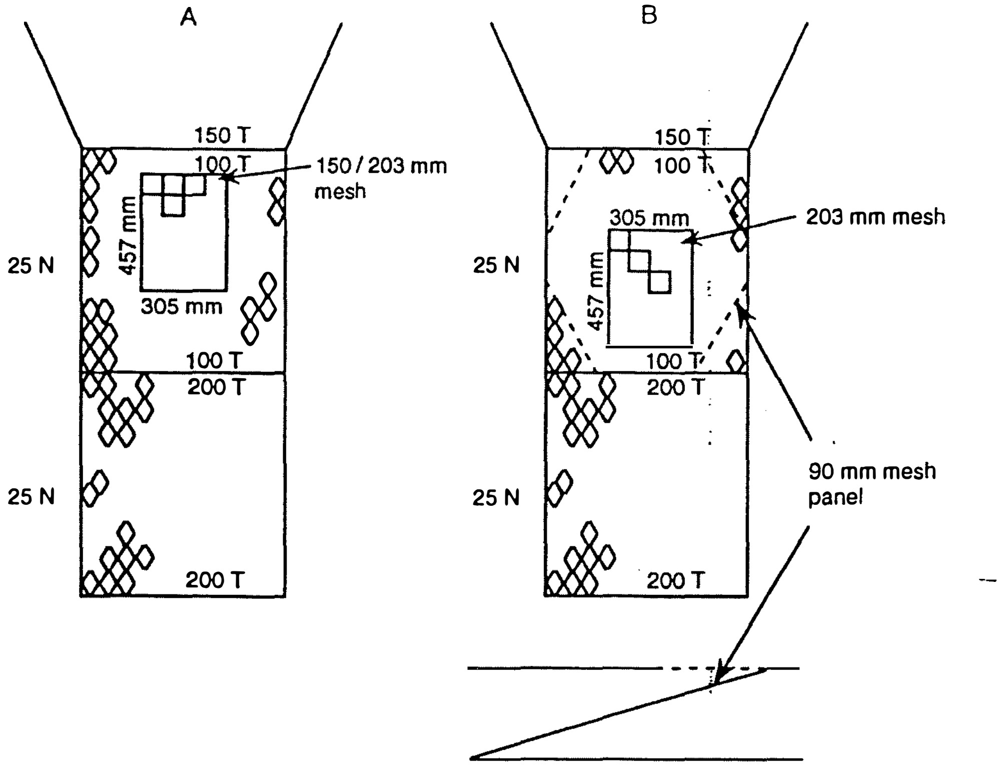

Fig. 3. Diagramatic representation of codends tested in Clarence River Experiment 2: (A) modified codends with panels of netting (150 mm and 203 mm respectively) cut on the bar and (B) 90 mm SPC.

Each modified codend was directly compared to the control codend, one on each net of the twin rigged gear. The position and order of each codend was randomly determined and each modified codend was used three times per day in normal commercial tows of between 14 and 41 minutes duration. Over 5 days during the trawling season, we completed a total of 15 replicate comparisons of each treatment codend against the control.

2.3. Botany Bay Experiment

In this experiment two modified codends were constructed that incorporated 100 mm and 150 mm separator panels respectively (termed the 100 mm SPC and 150 mm SPC), according to the specifications given above for the 90 mm SPC (see Fig. 4). The escape windows were made smaller (305 mm x 305 mm) than those described above. To facilitate removal of the codends, zippers (No. 10 nylon open-ended auto lock plastic slides) were attached to the net and each of the codends. The lengths of these zippers were calculated according to the methods described by Robertson (1986) for estimating the fishing circle circumference of codends.

The three codends were interchanged between tows in a random order so that each codend was used three times per night (total of nine tows per night). Over ten consecutive nights, we completed a total of 30 replicate tows (30 min duration) for each

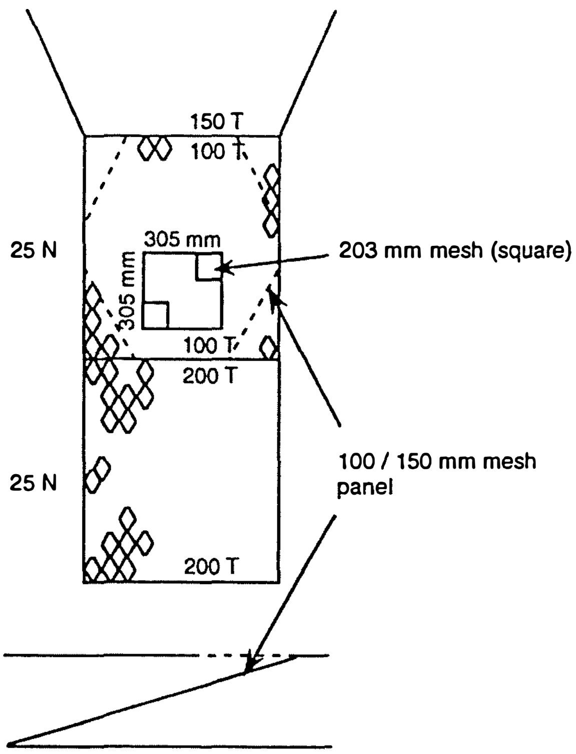

Fig. 4. Diagramatic representation of the 100 mm and 150 mm SPCs trialed in the Botany Bay Experiment and Clarence River Experiment 3.

of the three codends. To ensure independence among tows, the location of each tow was randomly selected from the available prawn-trawl locations that were possible under the particular conditions.

2.4. Clarence River Experiment 3

In this experiment, three modified codends were tested against the control. Two of the modified codends were the same as those used in the Botany Bay Experiment, except that the escape windows were left open (free of meshes) (Fig. 4). The third codend was constructed so that it incorporated a Nordmøre-grid scaled to fit the net (see also Isaksen et al., 1992) and located in a 2 m extension immediately anterior to the codend (Fig. 5). An identical 2 m extension of netting was constructed to be used with the control codend. All codends and extension pieces were fitted with zippers to facilitate changes.

Each of the modified codends was compared against the control in a random order four times per day in normal commercial tows of between 20 and 38 min duration. To ensure independence among tows, the location of each tow was randomly selected from the available prawn-trawl locations that were possible under the particular conditions. Over 4 days we completed a total of 16 replicate comparisons of each treatment codend against the control.

2.5. Data collected from the experiments

After each tow in each experiment, the codends were emptied on to a partitioned tray. All organisms were sorted according to species. Data collected from each tow were: the total weight of prawns, the total weight of by-catch, the weights, numbers and sizes of commercially and/or recreationally important finfish (to the nearest 0.5 cm), the numbers of non-commercial and/or non-recreational species and the total numbers of species in the assemblage. All prawns in a subsample of the total prawn catch from each tow were measured in the laboratory (to the nearest 1 mm carapace length).

Data from the Clarence River experiments for all replicates that had sufficient numbers of each variable were analysed in one tailed, paired *t*-tests (testing the hypothesis that the treatment caught less than the control).

Analysis of variance of differences between control and modified codends were done to provide a more detailed examination of the results from Clarence River Experiment 3. Firstly, to show there were no significant differences in tow duration between the various shots, the shot duration for each of the paired comparisons was analysed using Cochran's test for homogeneity of variances and the appropriate two factor analysis of variance (shot duration was non-significant at $P < 0.05$). Differences in catches between control and modified codends were then analysed using Cochran's test for homogeneity of variances and the appropriate two factor analysis of variance (Underwood, 1981). Significant differences detected in these analyses were investigated using Student–New-

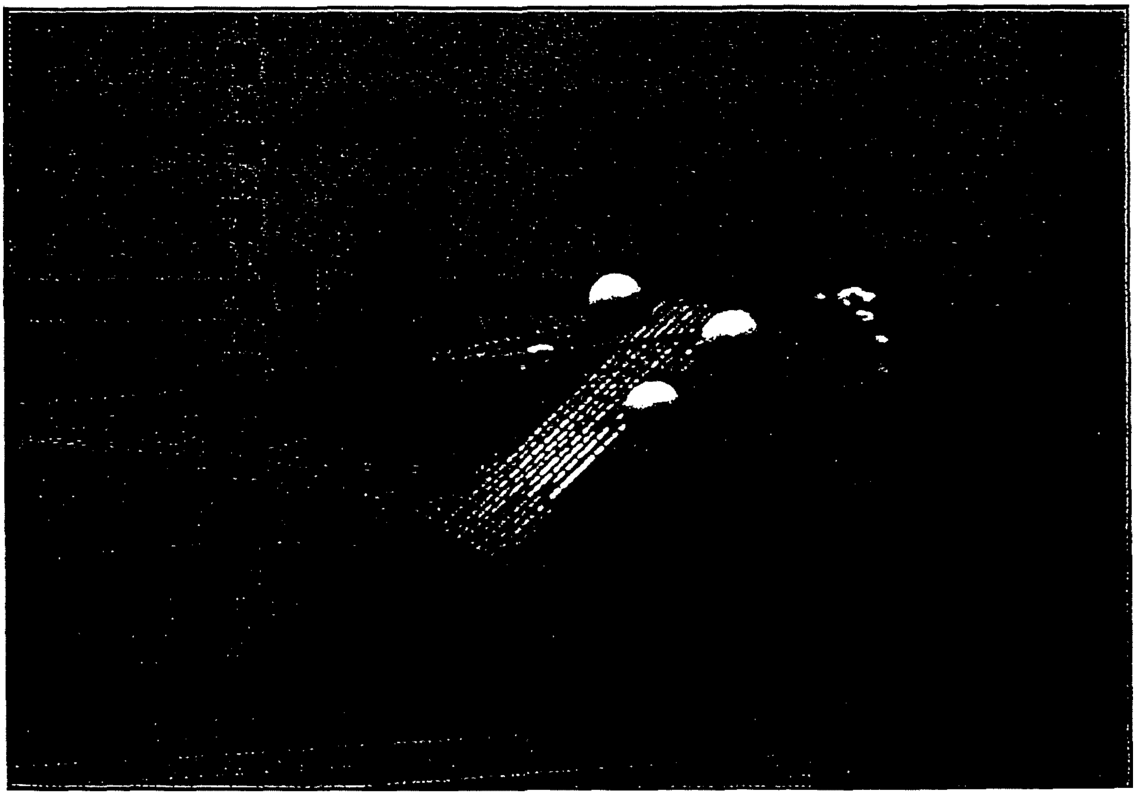

Fig. 5. Photograph of the Nordmøre-grid.

Table 1
Clarence River Experiment 1: summaries of one-tailed paired *t*-tests comparing different codends

	Control vs. 150 mm diamond mesh panel		Control vs. 203 mm diamond mesh panel		Control vs. 150 mm diamond mesh panel (frame)		Control vs. 203mm diamond mesh panel (frame)	
	Paired *t*-value	*P*	Paired *t*-value	*P*	Paired *t*-valve	*P*	Paired *t*-value	*P*
Weight of school prawns	−0.790	0.776	0.379	0.356	0.367	0.361	1.340	0.106
Weight of by-catch	−0.760	0.767	−1.209	0.872	1.490	0.085	−0.321	0.623
Number of bream	−0.611	0.722	−0.847	0.791	1.651	0.060	0.670	0.259
Weight of bream	−1.108	0.852	−1.011	0.839	1.775	0.054	1.121	0.145
Weight of catfish	0.892	0.197	1.505	0.083	1.154	0.139	−0.268	0.603
Number of non-commercial species	−1.369	0.898	−1.369	0.898	0.264	0.398	1.253	0.121
Total number of species	−1.274	0.883	−0.739	0.761	0.709	0.248	0.459	0.328

** Significant ($P < 0.01$); * Significant ($P < 0.05$).

man–Keuls multiple comparisons of means. Size-frequencies of school prawns and bream were graphed and compared using two-sample Kolmogorov–Smirnov tests ($P = 0.05$).

Data for all variables from the Botany Bay Experiment were analysed using Cochran's test for homogeneity of variances, transformed if necessary, and then analysed in the appropriate two factor analysis of variance. Significant differences detected in these analyses were investigated using Student–Newman–Keuls multiple comparisons of means. Size frequencies of king prawns were graphed and compared using two-sample Kolmogorov–Smirnov tests ($P = 0.05$).

3. Results

3.1. Clarence River Experiment 1

The four experimental codends used in Experiment 1 showed no significant differences from the control codend for any of the variables examined (Table 1).

3.2. Clarence River Experiment 2

The codends with the 150 mm and 203 mm mesh panels showed no significant differences from the control codend for any of the variables examined (Table 2). The 90 mm SPC, however, significantly reduced the weight of by-catch (mean reduction of 65%), the numbers and weights of bream (mean reduction of 65%), the numbers of non-commercial species (mean reduction of 35%) and the total number of species (mean reduction of 36%) (see Fig. 6(A), Fig. 6(B), Fig. 6(C), Fig. 6(D) and Table 2). This codend had no significant effect on the catch of school prawns (although the mean catch of school prawns was 77.3 g or 13% lower) (Fig. 6(E) and Table 2).

Two-sample Kolmogorov–Smirnov tests comparing the size–frequency distributions of bream from each sample (Fig. 7) showed no significant differences in the relative size

Table 2
Clarence River Experiment 2: summaries of one-tailed paired t-tests comparing different codends

	Control vs. 150 mm square mesh panel		Control vs. 203 mm square mesh panel		Control vs. 90 mm SPC	
	Paired t-value	P	Paired t-value	P	Paired t-value	P
Weight of school prawns	−0.487	0.683	1.412	0.090	1.247	0.116
Weight of by-catch	1.721	0.053	−0.534	0.700	5.066	0.001 **
Number of bream	−0.788	0.779	−0.233	0.591	2.769	0.007 **
Weight of bream	−0.375	0.644	−0.175	0.568	3.084	0.004 **
Number of non-commercial species	−1.193	0.874	1.000	0.167	5.358	0.0001 **
Total number of species	−0.138	0.554	1.524	0.075	4.432	0.0003 **

** Significant ($P < 0.01$); * Significant ($P < 0.05$).

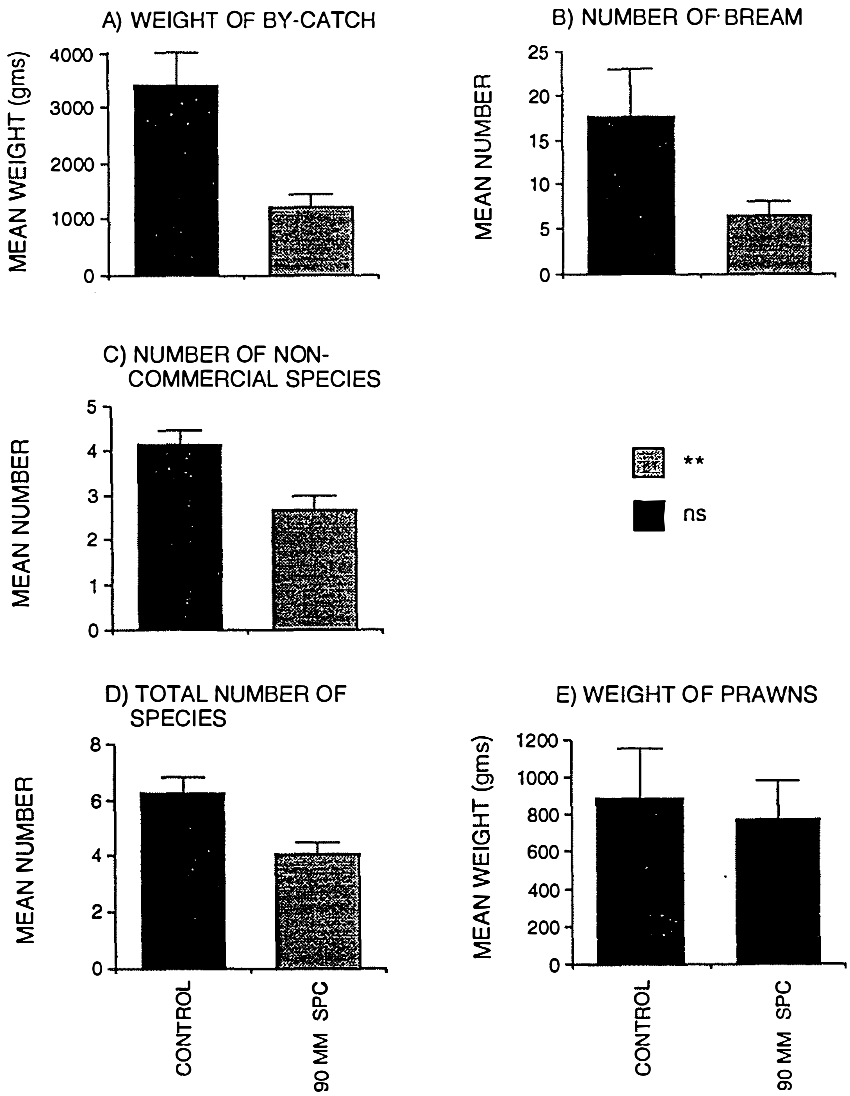

Fig. 6. Differences in mean catches ± SE between the control and 90 mm SPC tested in Clarence River Experiment 2: (A) the weights of by-catch; (B) the numbers of bream; (C) the numbers of non-commercial species; (D) the total number of species and (E) the weights of school prawns.

compositions between the 90 mm SPC and control codend. The data describing the size–frequency distributions of school prawns were incomplete and therefore excluded from analyses.

3.3. Botany Bay Experiment

Both codends with separator panels significantly reduced the weights of king prawns and by-catch, the numbers of non-commercial species and the total numbers of species compared to the control codend (Fig. 8(A), Fig. 8(B) and Table 3). The mean weights of king prawns and by-catch were reduced by 14.4% and 38% respectively in the 150 mm SPC, whilst the 100 mm SPC reduced these by 34% and 58.6% respectively (Fig. 8(A)

Table 3
Botany Bay Experiment: summaries of F ratios from analyses of variance to determine effects on variables due to fishing with different codends on different nights and of Student–Newman–Keuls multiple comparisons of means for those variables that showed significant differences between codends

Treatment	d.f.	Weight of king prawns raw	Weight of by-catch raw	Number of bar-tail goat fish $ln(x+1)$	Number of snapper $ln(x+1)$	No. of non-commerical species raw	Total number of species raw
Codends (C)	2	12.60 **	25.91 **	0.186	2.25	10.67 **	26.22 **
Nights (N)	9	2.57 *	1.35	7.92 **	5.67 **	6.24 **	10.72 **
C x N	18	1.32	0.91	0.81	0.64	1.25	1.73
Residual	60						

Weight of king prawns	Control > 150 mm separator panel > 100 mm separator panel
Weight of by-catch	Control > 150 mm separator panel > 100 mm separator panel
Number of non-commercial species	Control > 150 mm separator panel = 100 mm separator panel
Total number of species	Control > 150 mm separator panel > 100 mm separator panel

** Significant ($P < 0.01$); * Significant ($P < 0.05$). The transform used to stabilize variances (if required) is also given.

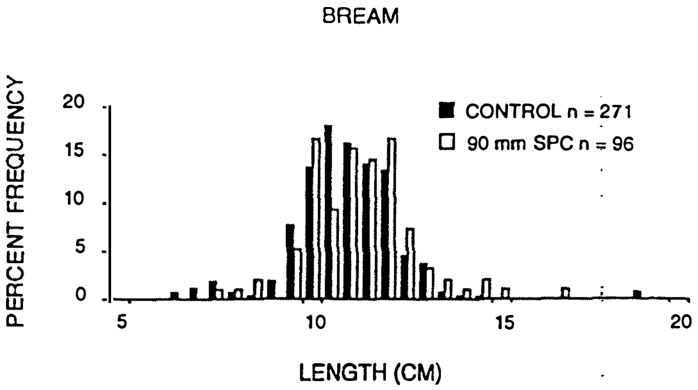

Fig. 7. Length–frequency distributions of bream from the control codend and the 90 mm SPC tested in Clarence River Experiment 2.

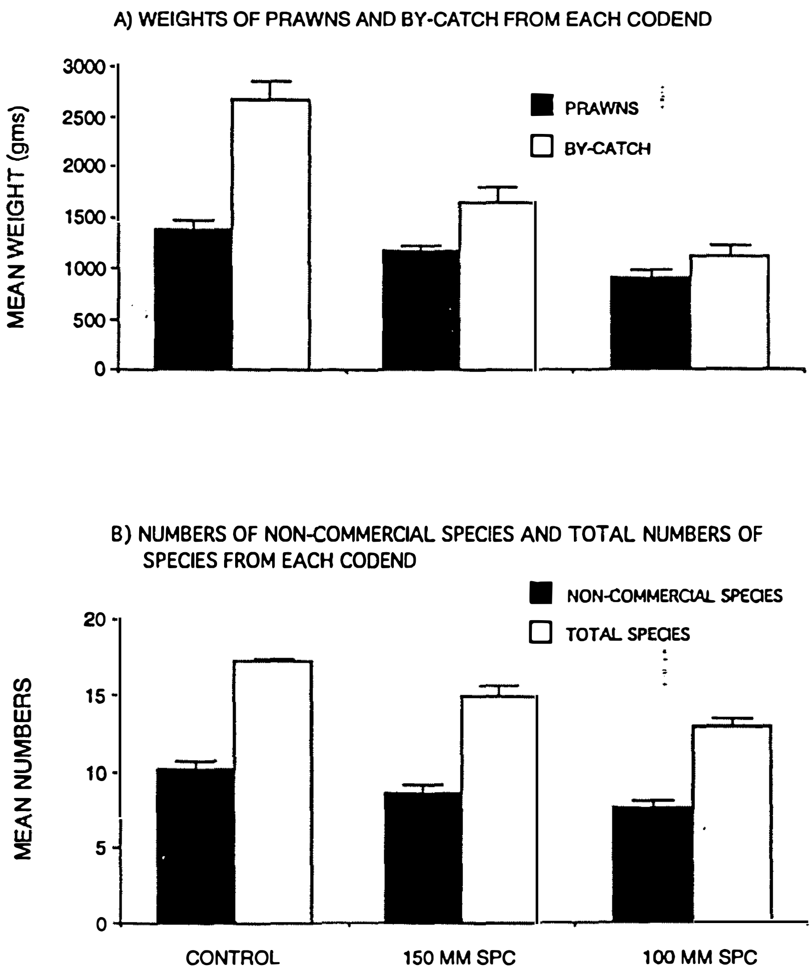

Fig. 8. Differences in mean catches ± SE (per 30 min tow) between the codends tested in the Botany Bay Experiment: (A) the weights of king prawns and by-catch and (B) the numbers of non-commercial species and total numbers of species ($n = 30$ for each codend pooled across days).

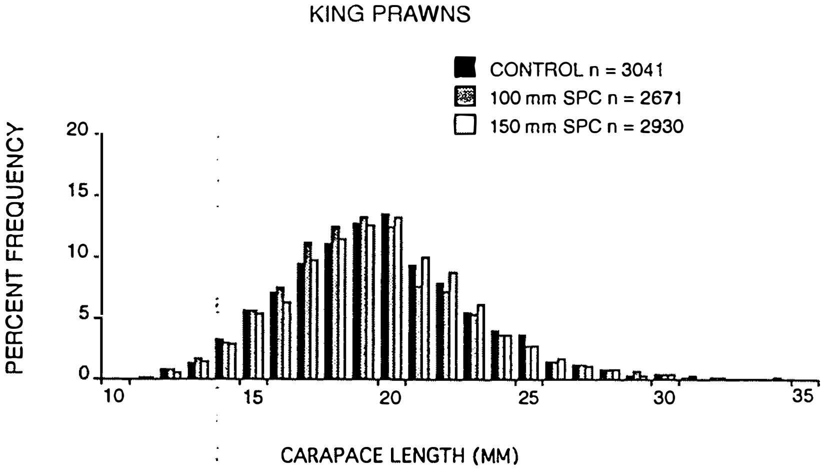

Fig. 9. Length–frequency distributions of king prawns from each of the three codends trialed in the Botany Bay Experiment.

and Table 3). The numbers of bar-tail goatfish (*Upeneus tragula*) and snapper showed significant differences among nights in the experiment but no effects due to codends (Table 3). No variables displayed significant interactions among the types of codend and nights.

Two-sample Kolmogorov–Smirnov tests comparing size–frequency distributions for the king prawns measured from each sample (Fig. 9) showed that whilst there were no differences in size compositions between the control and the 150 mm SPC, the 100 mm SPC caught proportionally fewer large prawns than both the control and the 150 mm SPC ($P < 0.05$).

3.4. Clarence River Experiment 3

All three modified codends significantly reduced the weights of by-catch, numbers and weights of bream and catfish (*Euristhmus lepturus*), the numbers of non-commercial species and the total numbers of species (Fig. 10(A), Fig. 10(B), Fig. 10(C), Fig. 10(D), Fig. 10(E) and Tables 4 and 5). Apart from a reduction in the weights of catfish retained in the net with the Nordmøre-grid, there were no other detectable differences in the rates of exclusion for each of the variables between the three modified codends (Table 6). Whilst none of the modified codends significantly reduced the catches of school prawns, the mean catches were 15% lower in the 100 mm SPC, 6% lower in the 150 mm SPC and 10% greater in the Nordmøre-grid (Fig. 10(F) and Table 4).

Two-sample Kolmogorov–Smirnov tests comparing the size–frequency distributions for bream measured from each sample showed no differences in the relative size compositions between the 150 mm SPC and control codend (Fig. 11(B)), whilst the 100 mm SPC and the Nordmøre-grid caught proportionally fewer large bream than their controls ($P < 0.05$) (Fig. 11(A) and Fig. 11(C)). The size–frequency distributions for school prawns showed that there were no significant differences between the SPCs and

Table 4
- Summaries of one-tailed paired t-tests comparing different codends for the Clarence River experiment No. 3.

	Control vs. 100 mm separator panel		Control vs. 150 mm separator panel		Control vs. Nordmøre grid	
	Paired t-value	p	Paired t-value	p	Paired t-value	p
Weight of school prawns	1.093	0.145	0.740	0.235	-0.767	0.773
Weight of by-catch	2.890	0.005 **	3.523	0.001 **	3.801	0.0009 **
No. of bream	2.499	0.012 *	2.257	0.019 *	3.304	0.002 **
Weight of bream	2.088	0.027 *	2.819	0.006 **	3.602	0.001 **
No. of catfish	1.977	0.033 *	2.823	0.006 **	1.878	0.040 *
Weight of catfish	2.283	0.018 *	1.916	0.037 *	2.807	0.006 **
No. of non-commercial species	4.869	0.0001 **	2.824	0.006 **	1.562	0.004 **
Total no. of species	6.143	0.0001 **	3.615	0.001 **	3.212	0.003 **

their controls while the Nordmøre-grid caught proportionally more medium sized school prawns (13–16 mm carapace length) and fewer large school prawns (Fig. 12).

4. Discussion

This series of experiments clearly illustrates that modifications to codends can selectively reduce the incidental catch of non-target species (see also Briggs, 1992; Isaksen et al., 1992; Broadhurst and Kennelly, 1994). By doing these trials in different fisheries, we have also shown that it is necessary to design such modifications on a fishery-specific basis (see also Watson et al., 1986; Averill, 1989; Rulifson et al., 1992).

In previous experiments, Broadhurst and Kennelly (1994); Broadhurst and Kennelly (1995) showed that square-mesh panels in codends were effective in releasing small fish (mulloway, *Argyrosomus hololepidotus*) from prawn-trawls in the Hawkesbury River. The characteristics of these designs were attributed to differences in the behaviour of fish and prawns in their response to stimuli from the trawl. That is, fish were thought to be herded together at the taper of the codend, invoking an escape response to the sides and top of the trawl (through the open mesh window). In contrast, benthic invertebrates like prawns were thought to display a limited response to stimuli from the trawl, were consequently forced against the meshes, and eventually tumbled down the net and into the back of the codend (Lochhead, 1961; Main and Sangster, 1985; Newland and Chapman, 1989).

In the present paper, the four modified codends from Clarence River Experiment 1 and the codends with the 150 mm and 203 mm mesh panels tested in Clarence River Experiment 2 were designed to take advantage of the above theory. They incorporated an escape panel of large mesh on top of the anterior section of the codend only, so that fish might escape without substantial loss of prawns. The results showed, however, that there was no evidence that fish escaped from any of these designs (Table 1). Possible reasons for these results are that the species caught in the Clarence River (predominantly bream) were not present in sufficient schooling densities and/or were not greatly affected by the stimuli from the trawl nor the hydrodynamic forces in the codend. This

Table 5
Summaries of mean reductions per tow and percentage reductions (between mean catches from modified and control codends) for each variable that showed a significant effect

	100 mm separator panel		150 mm separator panel		Nordmøre-grid	
	Mean reduction per tow	% difference	Mean reduction per tow	% difference	Mean reduction per tow	% difference
Weight of by-catch (g)	1528.75 ± 528.86	70.0	1452 ± 412.23	58.6	2038 ± 607.45	77.0
No. of bream	12.93 ± 5.17	52.5	5.37 ± 2.38	28.9	11.5 ± 3.48	52.2
Weight of bream (g)	443.75 ± 212.40	56.8	206.25 ± 73.16	35.5	485 ± 134.64	77
No. of catfish	4 ± 2.02	66.6	2.68 ± 0.95	53.1	8.43 ± 4.49	95.8
Weight of catfish (g)	214.38 ± 93.8	77.0	183 ± 95.91	58.2	631.25 ± 224.85	97.2
No. of non-commercial species	1.75 ± 0.36	29.5	1.18 ± 0.42	19.2	1.56 ± 0.50	26.4
Total no. of species	2.18 ± 0.35	28.0	1.94 ± 0.53	22.7	2.06 ± 0.64	26.4

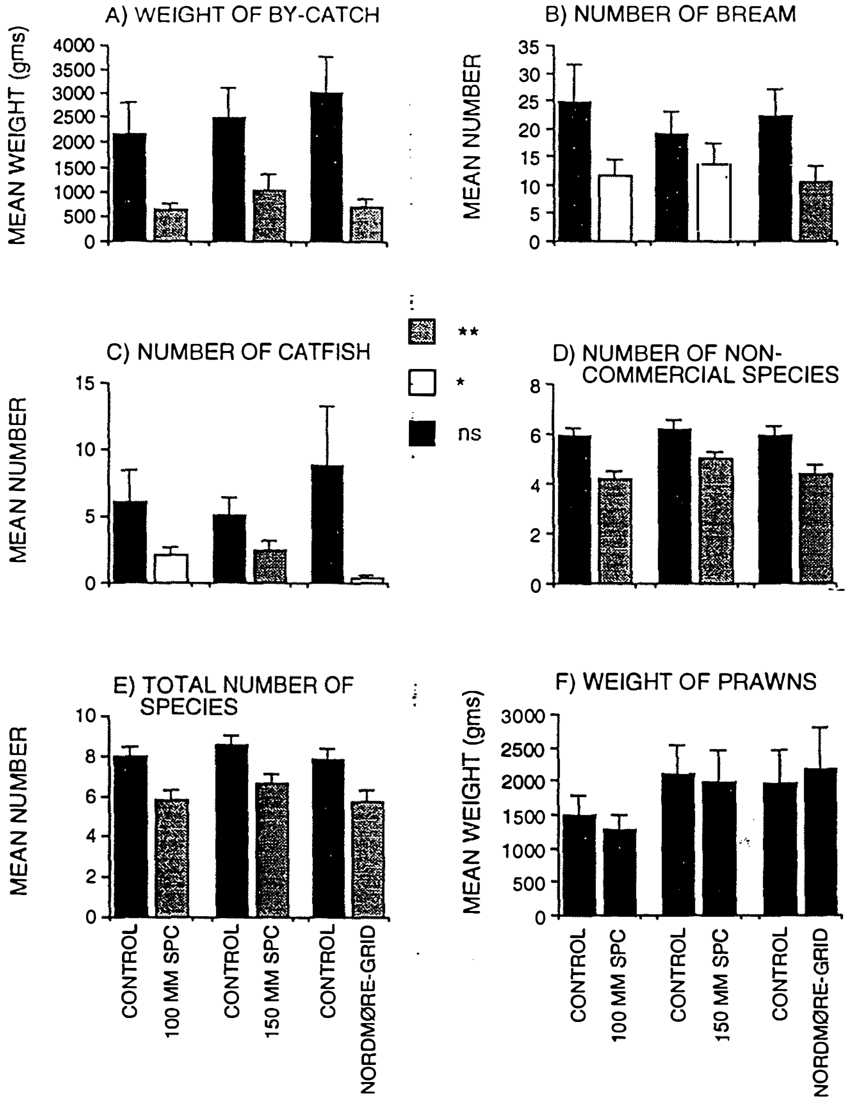

Fig. 10. Differences in mean catches ± SE between the codends tested in Clarence River Experiment 3: (A) the weights of by-catch; (B) the numbers of bream; (C) the numbers of catfish; (D) the numbers of non-commercial species; (E) the total number of species and (F) the weights of school prawns.

Table 6

Summaries of F ratios from analyses of variance to determine effects on variables due to fishing with different codends on different days for the Clarence River Experiment no. 3. The data were all treated in the raw form

Treatment	d.f.	Weight of school prawns	Weight of by-catch	No. of bream	Weight of bream	No. of catfish	Weight of catfish	No. of non-commercial species	Total no. of species
Codends (C)	2	1.00	0.92	1.09	1.06	1.12	3.30 *	0.42	0.05
Days (D)	3	0.87	2.15	2.43	2.86	1.50	1.84	0.56	0.24
C x D	6	0.61	1.25	0.36	0.59	1.00	2.14	1.00	0.65
Residual	36								

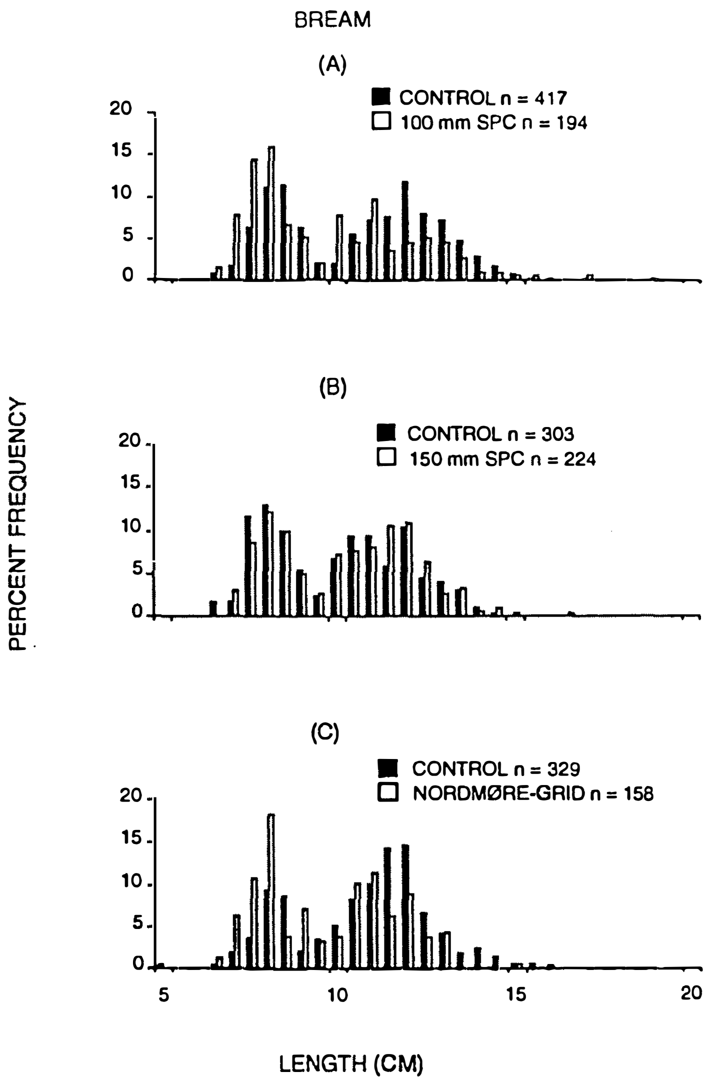

Fig. 11. Length–frequency distributions of bream from Clarence River Experiment 3: (A) the control and 100 mm SPC; (B) the control and 150 mm SPC and (C) the control and Nordmøre-grid.

latter hypothesis is supported by previous studies which have shown that physiological differences between species are a major factor in the effectiveness of escape panels (Robertson and Stewart, 1988; Briggs, 1992; Fonteyne and M'Rabet, 1992). Another hypothesis to explain these results is that the high dorsal profile of bream may have restricted their escape through the meshes in the escape window. Further, these fish may have maintained station in the codend, effectively masking the meshes of the escape window and preventing the escape of other smaller fish (see also Main and Sangster, 1991). The presence of other benthic material commonly found in the Clarence River (weed, sticks and assorted debris), may have a similar masking effect on these escape windows, contributing to the overall lack of fish exclusion.

None of the codends with escape panels significantly reduced the weights of school prawns (Table 1), supporting the theory that the response of benthic invertebrates to

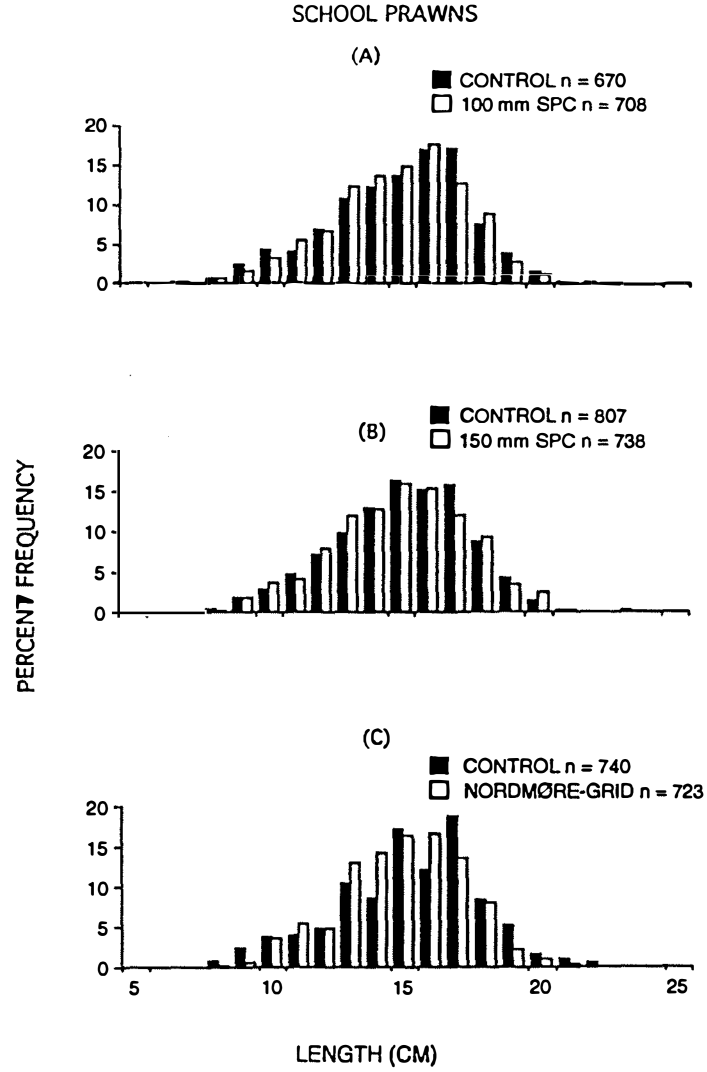

Fig. 12. Length–frequency distributions of school prawns from Clarence River Experiment 3: (A) the control and 100 mm SPC; (B) the control and 150 mm SPC and (C) the control and Nordmøre-grid.

stimuli from trawled gears is limited (see above and Lochhead, 1961; Main and Sangster, 1985; Newland and Chapman, 1989). This was seen as an important result in terms of the acceptance of this research by the prawning industry, since many believe that the large mesh panels in escape devices always lead to prawn loss.

The results from the 90 mm SPC tested in Clarence River Experiment 2 illustrated the effectiveness of inserting a soft separating panel into the codend (forward of the open mesh window) to divide prawns mechanically and direct by-catch upward through the window (Table 2 and Fig. 6). This codend significantly reduced the weight of by-catch (65%), and the weights and numbers of bream (65%) with no statistically significant effect on the catch of school prawns (although the mean catch was 13% lower, see Fig. 6). It is reasonable to assume that the separating panel in this codend physically directed those by-caught organisms that were larger than the 90 mm mesh size used in the separator panel through the window. For bream, however, despite a significant reduction in numbers (65%), Kolmogorov–Smirnov tests on size–frequency compositions failed to detect any difference between the control and 90 mm SPC (Fig. 7), suggesting that the exclusion of these fish occurred across the range of sizes sampled (5–20 cm). Perhaps some small bream detected the panel in advance (either visually or using their lateral lines) and orientated away from the stimuli. The geometric attitude of the panel would have directed some of these fish out of the codend, whilst others simply passed through the panel and into the rear of the codend. The retention of larger bream in the codend (> 13 cm) may have been caused by masking of the escape window by weed (see above), preventing these fish from escaping and forcing them through the meshes of the separator panel.

The size of mesh in the separator panel used in the 90 mm SPC may have contributed to the mean reduction in school prawn weight (13%, see Fig. 6(E)). It is possible that this mesh-size was too small and/or the presence of weed and debris closed the meshes in the panel, allowing some prawns to tumble out through the window.

Increasing the size of mesh in the separator panel to 100 mm and 150 mm showed different results in different locations. The 100 mm and 150 mm SPC tested in the Botany Bay Experiment significantly reduced the total weights of by-catch (58.6% and 38% respectively) and king prawns (34% and 14% respectively) with no significant effect on the by-catch of fish such as snapper and bar-tailed goat fish (Table 3). These comparatively poor exclusion characteristics might be attributed firstly to the size and type of species by-caught in this estuary. Because much of this by-catch consisted of small fish and crustacea that were similar in size to the targeted prawns, many could not be excluded from the trawl simply using size-based separator panels. Secondly, because this is a nocturnal fishery, many of the smaller fish may not have detected the separating panel visually in sufficient time to be directed out of the codend.

In the Clarence River, the 100 mm and 150 mm SPCs reduced the weights of by-catch (70% and 58.6% respectively), and all other variables with no significant reductions in the weights of school prawns caught (although the means were reduced by 15% and 6% respectively, see Fig. 10). Whilst Kolmogorov–Smirnov tests detected a difference in the size-compositions of bream between the 100 mm SPC and its control, this modified codend, along with the 150 mm SPC still retained a number of larger bream (see Fig. 11(A) and Fig. 11(B)). The exclusion of bream from these modified codends may be explained using the theory discussed above for the 90 mm SPC.

Differences in the prawn-retention characteristics of these modified codends between the two locations (i.e. significant reduction of king prawns in Botany Bay but not school prawns in the Clarence River) may reflect interspecific variabilities. Although Broadhurst and Kennelly (1994) suggest that these species exhibit a similar response to stimuli from the trawl, in terms of their behaviour during capture, their levels of endurance and degree of abdominal flexion and extension may differ. King prawns were observed to be more active when the codends were emptied onto the sorting tray, jumping and 'flipping' for up to a minute. It is possible that this species 'flips' more frequently in the trawl, increasing the likelihood of escape through the open mesh window.

The only modified codend that did not show any reduction in mean prawn catches was that containing the Nordmøre-grid, tested in Clarence River Experiment 3 (Fig. 10

Table 7
Summary of Student-Newman-Keuls multiple comparisons of the weights of catfish.

Weight of catfish	100 mm separator panel = 150 mm separator panel > Nordmøre-grid

and Table 4). This design reduced the weights of by-catch (by 77%), numbers and weights of bream (52% and 77% respectively), numbers and weights of catfish (95.8% and 97.2%) and the numbers of non-commercial species and total species (26.4% each) (see Table 5). Although analysis of variance and SNK tests failed to detect any differences between the Nordmøre-grid and the 100 mm and 150 mm SPCs (apart from a reduction in catfish weights, see Table 7), in addition to the prawn retention characteristics, there are at least two reasons why the grid seemed to have the most potential for development and application in the Clarence River. Firstly, the rigid structure and fixed bar spacings appeared to provide more accurate size-separation of individual species, increasing the likelihood of excluding individuals larger than a certain size. The 20 mm spacings used in the grid in this experiment, for example, excluded virtually all bream > 13 cm with no loss of school prawns (Fig. 11(C)). Secondly, the rigid shape and smooth contours of the grid exclude weed and debris more effectively. This is perceived by industry as a problem at certain locations in the river, restricting the area available for trawling and the duration of tows.

This series of experiments showed that there exists great potential for the eventual development of modified codends for use in N.S.W.'s estuarine prawn-trawl fisheries which will exclude a large proportion of juvenile fish with minimal loss of prawns. The differences in the results from the two estuaries examined suggest that different fisheries, with different target and by-catch species and environmental parameters, require modifications to codends that are unique to each.

While the advantages of using the sorts of modifications developed in this paper appear obvious, the ultimate effectiveness of these designs in terms of conserving juveniles of commercially and/or recreationally important species is determined by the extent of post-trawl mortalities associated with escaping through panels of mesh and along the bars of solid grids. Although other studies suggest that these effects may be minimal, (Main and Sangster, 1988; DeAlteris and Castro, 1992), future research should include an assessment of this question on a species-specific and fishery-specific basis, before concluding that designs such as these will solve the potential impacts that prawn trawling has on other commercial and recreational fisheries.

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Abstract

Effects on the escape of small fish from prawn-trawl codends due to (i) codend circumference and (ii) a new design of square-mesh panel were investigated in the New South Wales oceanic prawn-trawl fishery. Simultaneous comparisons of two conventional diamond-mesh codends, constructed with posterior sections of 100 and 200 meshes circumference, respectively, showed that halving this circumference significantly altered the selectivity of the codend and decreased the by-catch of small fish. A new design of square-mesh panel incorporated composite panels of netting (60 mm and 40 mm mesh), sewn in such a way that the meshes were square-shaped and inserted into the top of the anterior section of the codend. This panel was designed to allow larger fish to escape through the 60 mm mesh (at the point where waterflow was thought to be the greatest) and also increase the random escape of smaller individuals through the 40 mm mesh. To determine any influences of codend circumference on the performance of this panel, it was inserted into two codends with posterior sections of 100 and 200 meshes circumference, respectively. Simultaneous comparisons with each other and with their controls showed that the two-panelled codends, with posterior sections of both 100 and 200 meshes, performed similarly and significantly reduced the weights of discarded by-catch without significantly reducing the catch of prawns. There was evidence that more fish tended to escape through the square-mesh panel in the codend with the posterior section of 200 meshes circumference. The results are discussed in terms of the effects that codend circumference (and therefore hydrodynamic pressure) may have on the escape of small fish through codends that do/do not have square-mesh panels.

Keywords: By-catch reduction; Codend circumference; Prawn-trawl; Square-mesh

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1. Introduction

Oceanic prawn-trawling occurs from 11 major ports in New South Wales (NSW) Australia, and is valued at approximately A$17 million per annum. The principal target species for this fishery is the eastern king prawn, *Penaeus plebejus*, although a significant portion of the total value in the fishery is derived from the sale of legally retained by-catch (termed 'by-product') comprising several species of fish, crustacea and cephalopods (see Kennelly, 1995). As with most trawl fisheries, however, significant numbers of non-target organisms are also captured and discarded. This subset of by-catch includes individuals of by-product species which are smaller than the minimum commercial size, in addition to juveniles of species caught in other commercial and recreational fisheries (see Kennelly, 1995).

Although there is little information on the post-trawl mortalities of the key by-catch species in NSW, the quantities involved have raised significant concerns over the potential for negative impacts of prawn-trawling on future stocks of these species (see Kennelly, 1993). These concerns led to investigations of various modifications to trawls and trawling practices that minimise undesirable by-catch whilst maintaining catches of commercial species (i.e. prawns and by-product).

Several trawl fisheries throughout the world have alleviated problems of undesirable by-catch by inserting panels of square-mesh in the codends of trawls (Robertson, 1983; Isaksen and Valdermarsen, 1986; Robertson and Stewart, 1988; Carr, 1989; Suuronen, 1990; Briggs, 1992; Broadhurst and Kennelly, 1994; Broadhurst and Kennelly, 1995). In previous experiments (Broadhurst and Kennelly, 1994; Broadhurst and Kennelly, 1995), we showed that small square-mesh panels inserted into anterior sections of codends allowed small fish to escape without significant loss of prawns. The results from these designs were attributed primarily to differences in the behaviour of fish and prawns in the trawl. Fish were thought to be herded together in the anterior section of the codend, upsetting the balance of the school and initiating an escape response towards the sides and top of the net and out through the open square-shaped meshes. A contributing factor towards the escape of these fish was thought to be the attachment of an anterior codend panel of 100 meshes circumference to a posterior codend panel constructed of heavy twine and 200 meshes circumference (normal commercial configuration). It was hypothesised that the increase in twine area in the posterior panel resulted in a difference in hydrodynamic pressure anterior to this panel, stimulating the lateral line receptors of the fish and contributing to their overall escape response. The reaction of prawns to this stimulus was thought to be minimal, given their inability to sustain escape responses to trawls (see Lochhead, 1961; Newland and Chapman, 1989). Because the differences in hydrodynamic pressure were thought to be greatest at the point of attachment of the two panels, it was suggested that the insertion of a relatively small panel of square-mesh in this area would be adequate to exclude a large number of small fish.

In a recent experiment examining the effects of haulback-delay (the duration between slowing the vessel and engaging the hauling winch) on the rates of escape of small fish from square-mesh panels (Broadhurst et al., 1996), we tested two designs of codend with small panels of square-mesh (11 × 7 bars of 85-mm mesh) constructed according to the theory discussed above. The results showed that the level of stimuli required to promote an escape response from the trawl varied among species, possibly due to subtle differences in their physiology and behaviour (see also Robertson and Stewart, 1988; Briggs, 1992). For example, while most species escaped continuously during the tow (perhaps according to the theory above), the majority of an important commercial species (red spot whiting *Sillago flindersi*) remained in the codend, only escaping through the panel of square-mesh when additional stimuli were generated during the delay in haulback. This result raised some concerns over the potential mortality of these individuals during towing, and led to the present paper which examines designs of codends that promote escape throughout the duration of towing.

The results from the papers discussed above showed that to develop appropriate designs of square-mesh panels that exclude individuals continuously during towing, it is necessary to have information on species-specific behavioural responses to the trawl and, where possible, to identify stimuli which evoke such responses. Our goals in the present paper were: (i) to investigate the effectiveness of a new design of square-mesh panel in reducing several species of by-catch continuously throughout the tow, and (ii) to examine the effects that the circumference of the posterior panel of the codend has on the escape of fish through codends that do and do not contain square-mesh panels.

2. Materials and methods

This study was done in March 1995 on commercial prawn-trawl grounds north-east of Iluka, New South Wales (29°26′S, 153°22′E) using a 17 m commercial prawn-trawler. Three florida flyers (mesh size 42 mm), each with a headline length of 15.8 m, were rigged in a standard triple gear configuration (see Kennelly et al., 1993, for details), and towed at 2.5 knots. Each of the identical outside nets were rigged with zippers (No. 10 nylon open-ended auto-lock plastic slides) to facilitate changing the codends. Because the middle net was not rigged in exactly the same way as the outside nets (see Kennelly et al., 1993 for details), it was excluded from any analysis.

The codends used in the experiment measured 58 meshes long (2.3 m) and were constructed from 40 mm mesh netting and 60-ply twine (Fig. 1). These codends comprised two panels: the anterior panel was 33 meshes long and attached to a zipper; the posterior panel was 25 meshes long. Four designs of codend were compared. The first and second codends (termed the 100 control and 200 control codends) were made entirely of diamond-shaped meshes and comprised anterior panels with a circumference of 100 meshes, attached to posterior panels with circumferences of 100 and 200 meshes, respectively (Fig. 1(A)). The third and fourth codends (termed the 100 panel and 200 panel codends) were similar to their respective controls in construction (i.e. the 100 and 200 control codends), but included composite panels made of 60 mm and 40 mm netting cut on the bar and inserted into the top of the anterior section (Fig. 1(B)). We predicted that: (i) large numbers of fish would escape through the panel of 60 mm square-mesh, placed at the point where waterflow was thought to be the greatest; and (ii) the 40 mm square-mesh anterior and lateral to this panel would increase the random escape of smaller fish.

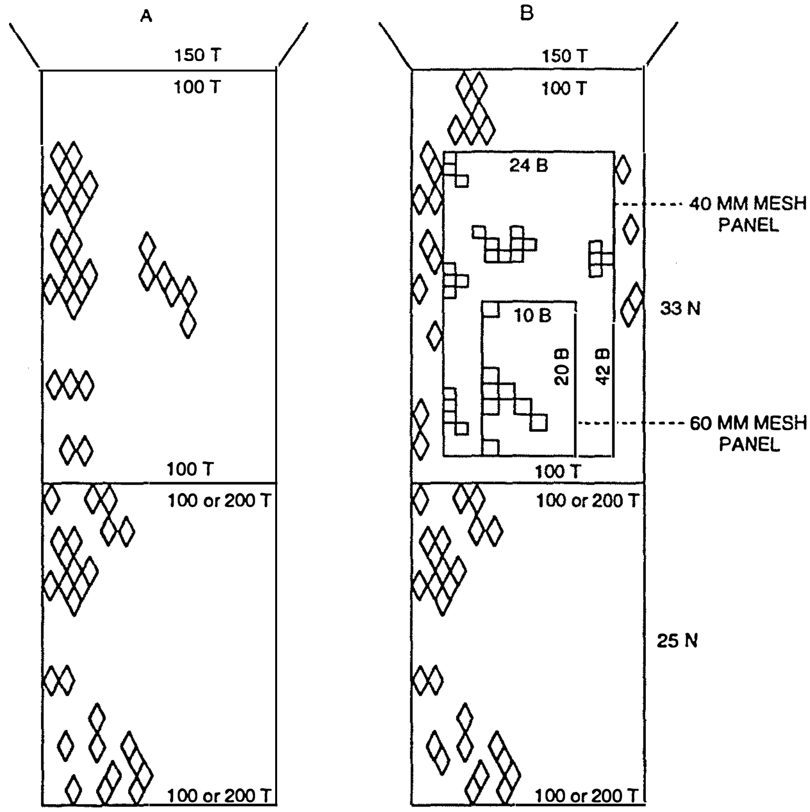


Fig. 1. Diagrammatic representation of (A) the 100 control and 200 control codends, and (B) the 100 panel and 200 panel codends.

All four codends were compared against each other in independent paired trials. That is, in separate tows, both codends with the square-mesh panel were compared against each other and their respective controls, and the control codends were also compared against each other. The particular pair to be compared in a given tow were placed on each outside net of the triple-rigged gear. The position and order of each codend was determined randomly (to eliminate any biases between different trawls and sides) and used in normal commercial tows of 75 min duration. Because some significant effects of haulback-delay were quantified in a previous experiment (Broadhurst et al., 1996) and we wanted to test the effectiveness of the modified codends in excluding fish throughout the duration of towing, all tows were performed with no delay in haulback. The location of each tow was randomly selected from the available prawn-trawl locations that were possible under the particular conditions. Over eight nights we completed a total of ten replicates for each of the four paired comparisons.

After each tow, the two codends were emptied onto a partitioned tray. Prawns and all commercially important species larger than the minimum legal size (retained commercials) were separated. The remaining by-catch (termed discarded by-catch) was then sorted. This included individuals of commercially important species that were smaller than the minimum legal size (discarded commercials). Data collected from each tow were the total weight of prawns and their sizes (to the nearest 1 mm carapace length), the weight of the discarded by-catch, the weights, numbers and sizes (to the nearest 0.5 cm) of retained and discarded commercial species, the weights and numbers of the most commonly occurring non-commercial species, and the numbers of commercial species in the assemblage. Several commercially important species were caught in sufficient quantities to allow meaningful comparisons. These were eastern king prawns, octopus, *Octopus* spp., smooth bugs, *Ibacus* sp., red spot whiting, *Sillago flindersi*, stout whiting, *Sillago robusta*, and eastern blue spot flathead, *Platycephalus caeruleopunctatus*. A non-commercial species, long-spined flathead, *Platycephalus longispinis*, was also caught in sufficient quantities to permit analyses.

Data for all replicates that had sufficient numbers of each variable (> 2 fish in each comparison) were analysed in one-tailed, paired *t*-tests (the hypotheses tested were: 100 panel < 100 control; 200 panel < 200 control; 100 panel < 200 panel; 100 control < 200 control). Except for stout whiting, where analyses provided similar results for weights and numbers of taxa, only data about numbers were included in the figures to conserve space. Size–frequencies of prawns, stout whiting and red spot whiting (where there were sufficient numbers) were plotted and compared using two sample Kolmogorov–Smirnov tests ($p = 0.05$).

3. Results

Compared with their respective controls, both the 100 panel and 200 panel codends significantly reduced the weights of discarded by-catch (means reduced by 35.1% and 40.1%, respectively) with no significant reduction in catches of prawns (Fig. 2(A,B) and Table 1). The mean numbers and weights of discarded stout whiting were significantly reduced by 49.5% and 55.5% in the 100 panel codend, whilst the 200 panel codend reduced these amounts by 64.3% and 55.7%, respectively (Fig. 2(C,D) and Table 1). The mean numbers and weights of long-spined flathead were also reduced in the 100 panel codend (by 33.2% and 36.1%) and the 200 panel codend (by 59.3% and 46.7%) (Fig. 2(E) and Table 1).

Comparing the two codends with the square-mesh panel showed a significant reduction in the numbers and weights of discarded stout whiting by the 100 panel codend (by 57.4% and 47.2%) (Fig. 2(C,D) and Table 1).There were no other significant differences, although the mean weight of discarded by-catch and numbers of long-spined flathead were reduced by 20.0% and 34.4%, respectively.

Compared with the 200 control, the 100 control significantly reduced the weight of by-catch (mean reduced by 40.1%), the numbers and weights of discarded stout whiting (by 61.9% and 46.9%), the numbers and weights of long-spined flathead (by 62.7% and 63.5%) and the numbers and weights of retained octopus (by 40.2% and 31.5%) (Fig. 2(B–E,G) and Table 1). There was no detectable difference in prawn catches between the two control codends (Fig. 2(A) and Table 1).

Two-sample Kolmogorov–Smirnov tests comparing the size–frequency distributions for prawns measured from each sample showed no differences in the relative size-compositions between any of the codends tested (Fig. 3). Significant differences were detected in the size-compositions of stout whiting between the codends tested (Fig. 4).

The 100 control codend caught proportionally more medium-sized stout whiting than the 100 panel codend (Fig. 4(A)), while the 200 control caught proportionally more small-sized stout whiting than the 200 panel codend (Fig. 4(B)). Both the 200 control and the 200 panel codends retained proportionally more small-sized stout whiting than the 100 control and 100 panel, respectively (Fig. 4(C,D)). The size–frequency distribu-

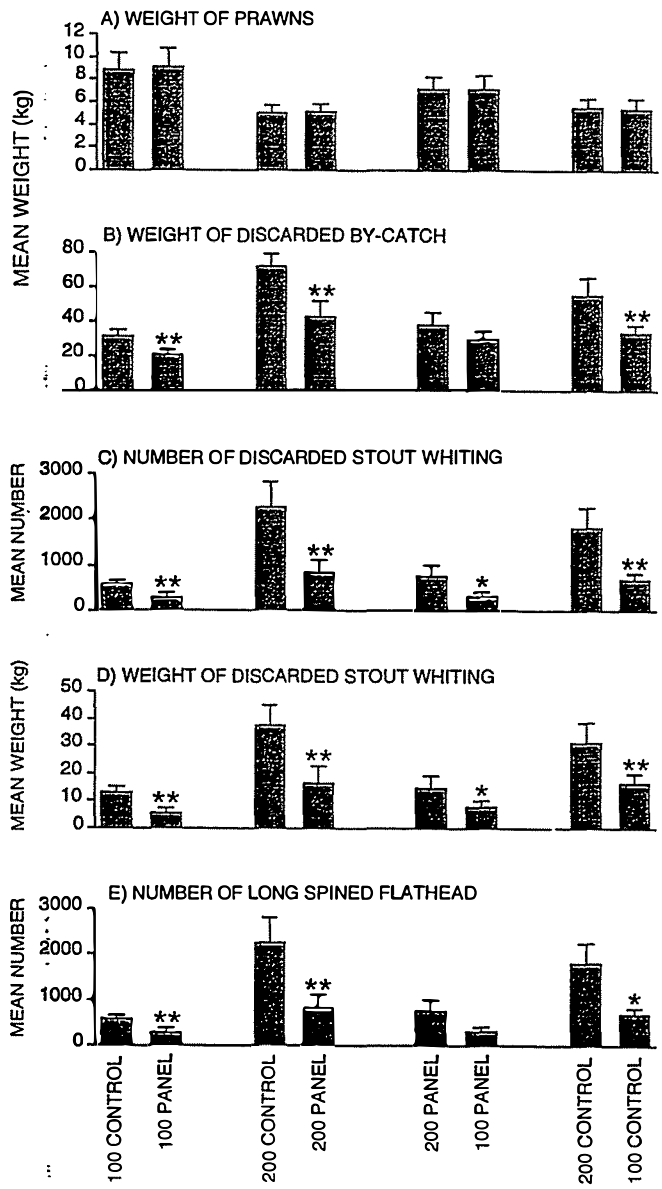
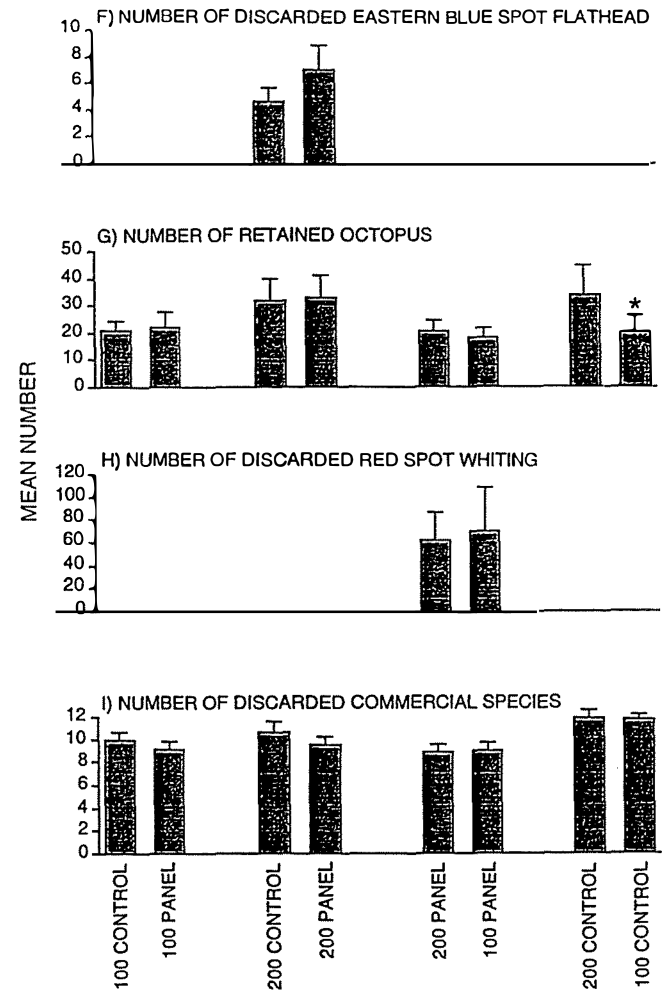


Fig. 2. Differences in mean catches ± SE between each of the codends tested in the experiment: (A) the weights of prawns; (B) the weights of discarded by-catch; (C) the numbers of discarded stout whiting; (D) the weights of discarded stout whiting; (E) the numbers of long-spined flathead; (F) the numbers of discarded eastern blue spot flathead; (G) the numbers of retained octopus; (H) the numbers of discarded red spot whiting; (I) the numbers of discarded commercial species. ** Significant at $p < 0.01$; * significant at $p < 0.05$.



tions for red spot whiting showed that the 200 panel codend retained significantly more small red spot whiting than the 100 panel codend (Fig. 4(E)).

4. Discussion

The data presented here showed that both codends with the square-mesh panel were effective in allowing non-target species to escape continuously throughout the duration of towing, with no effect on the catches of prawns or commercial by-product. By comparing the control codends against one another and also against both codends with square-mesh panels, we have detected some possible influences on the escape of fish through these codends due to changes in the geometry of the codends and corresponding hydrodynamic forces.

The results of the comparisons between codends with large and small circumferences showed that, compared with the 200 control, the 100 control codend significantly

Table 1
Summaries of one-tailed paired t-tests comparing different codends

	100 control vs. 100 panel, p	200 control vs. 200 panel, p	200 panel vs. 100 panel, p	200 control vs. 100 control, p
Wt. of prawns	0.788	0.770	0.554	0.396
Wt. of discarded by-catch	**0.0007**	**0.0004**	0.076	**0.0005**
No. of retained octopus	0.598	0.573	0.178	**0.015**
Wt. of retained octopus	0.304	0.833	0.607	**0.017**
No. of discarded smooth bugs	0.681	0.249	0.162	0.655
Wt. of discarded smooth bugs	0.733	0.199	0.340	0.154
No. of discarded rsw	–	–	0.399	–
Wt. of discarded rsw	–	–	0.612	–
No. of discarded stout whiting	**0.0002**	**0.002**	**0.033**	**0.004**
Wt. of discarded stout whiting	**0.0002**	**0.001**	**0.040**	**0.003**
No. of discarded ebs	–	0.870	–	–
Wt. of discarded ebs	–	0.885	–	–
No. of long-spined flathead	**0.025**	**0.007**	0.114	**0.011**
Wt. of long-spined flathead	**0.007**	**0.021**	0.203	**0.027**
No. of discarded commercial spp.	0.236	0.164	0.553	0.572

Significant p values are in bold type; (–) insufficient data; rsw, red spot whiting; ebs, eastern bluespot flathead; weights in kilograms.

reduced the weights of by-catch (by 40.1%), the numbers and weights of stout whiting (by 61.9% and 46.9%, respectively) and the numbers and weights of long-spined flathead (62.7% and 63.5%, respectively) (see Fig. 2 and Table 1). These results confirm the findings of previous studies which have shown that reducing the circumference of a codend made of diamond-shaped meshes increases the lateral openings of these meshes and so allows more fish to pass through the netting (Robertson and Stewart, 1988; Armstrong et al., 1990; Reeves et al., 1992; Galbraith et al., 1994).

By adding a strategically placed square-mesh panel to these codends with large and small circumferences, we detected trends similar to those described above (i.e. a reduction in mean weights and numbers by the 100 panel codend compared with the 200 panel codend). However, for most variables these effects were much smaller than those detected for the codends without square-mesh panels, to the point where the differences were statistically non-significant (see Table 1). For example, compared with the 200 control, the 100 control significantly reduced the mean weight of discarded by-catch and the numbers of long-spined flathead by 40.1% and 62.7%, respectively (see above). With the square-mesh panel in place, however, the mean differences between these two codends for these variables were only 20.0% and 34.4%, respectively (Fig. 2). If the selectivity of the posterior section of the 100 panel codend was similar to that of the 100 control codend discussed above (i.e. meshes with large lateral openings), then small fish entering the 100 panel codend probably escaped through the open square-meshes in the panel *and* the open diamond-meshes in the posterior section. However, because the meshes in the posterior section of the 200 panel codend were probably closed, sufficiently more fish must have passed through its square-mesh panel to give the small

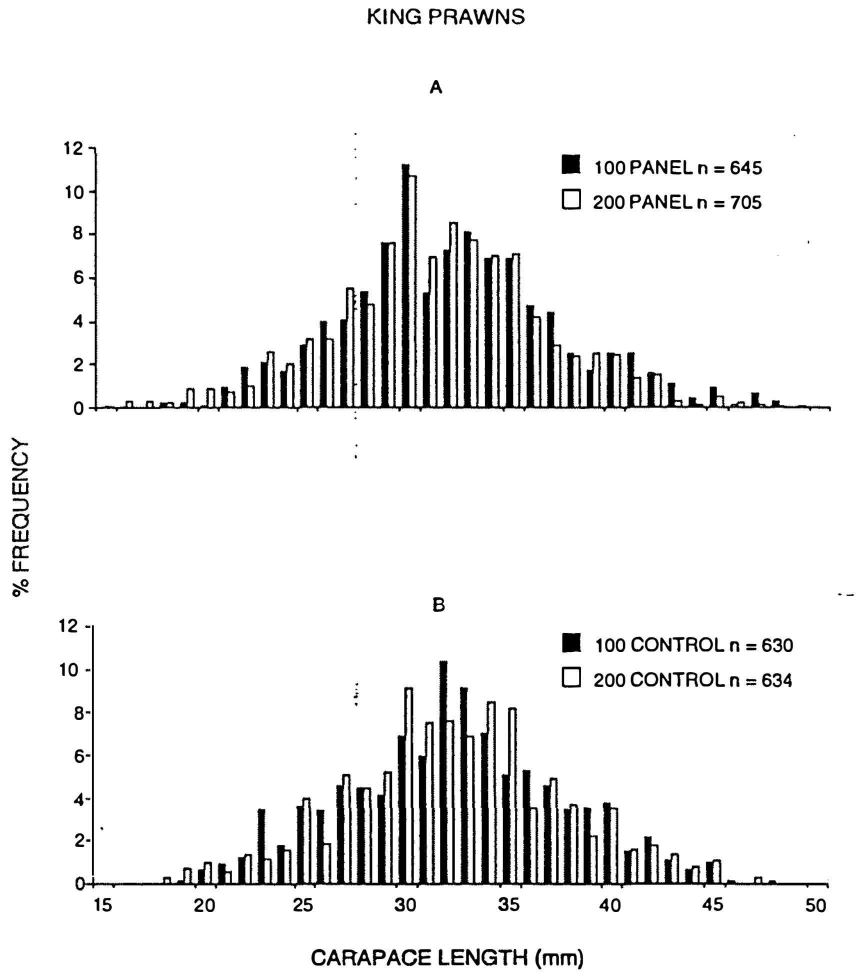


Fig. 3. Size–frequency distributions of king prawns, *Penaeus plebejus*, from (A) the 100 panel and 100 control codends, and (B) the 100 control and 200 control codends.

(and non-significant) differences detected between the 100 and 200 panel codends. This effect may have been caused by a decrease in water flow towards the rear of this codend due to the closed meshes, and a corresponding increase in water flow out through the meshes ahead of this section (see also Watson, 1989). Such a water flow may have either actively assisted in the escape of some free-swimming fish by directing them out through the strategically positioned 60 mm square mesh panel and/or stimulated their lateral line receptors which enhanced their overall escape response.

Whilst this effect was evident for red spot whiting, long-spined flathead and the individuals of species comprising discarded by-catch, it did not occur for stout whiting, whose numbers were reduced by similar levels in codends with 100 and 200 meshes circumferences, irrespective of the presence of a square-mesh panel (57.4% and 61.9%, respectively; Fig. 2). For this species, schooling density and abundance may have affected their escape through the square-mesh panels.That is, the large numbers of stout whiting encountered during each tow (approximately 1000 fish per net) were probably herded close together in the narrow anterior sections of both the 100 and 200 panel

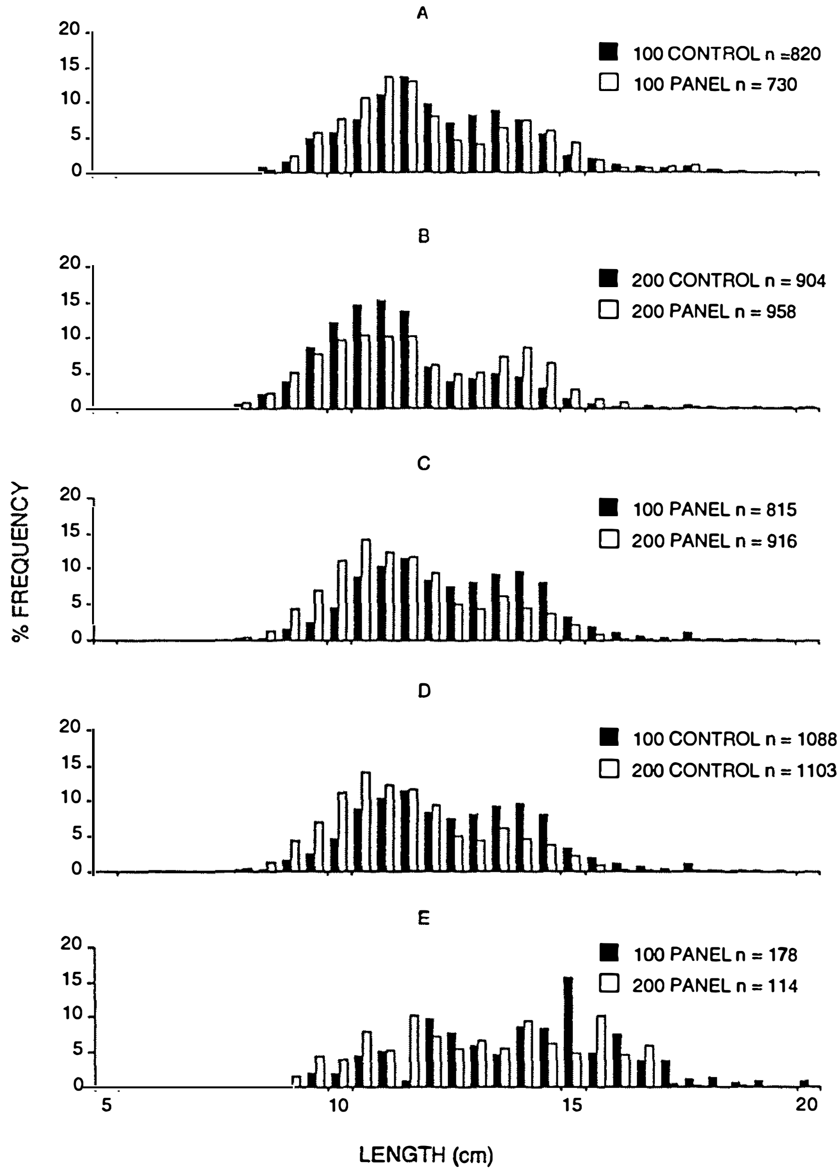


Fig. 4. Size–frequency distributions of stout whiting, *Sillago robusta*, from: (A) the 100 control and 100 panel codends; (B) the 200 control and 200 panel codends; (C) the 100 panel and 200 panel codends; (D) the 100 control and 200 control codends. (E) Size–frequency distributions of red spot whiting, *Sillago flindersi*, from the 100 panel and 200 panel codends.

codends, which may have upset the balance of the schools and initiated an escape response towards the sides and top of the net–prior to any effects of water flow further down the codend (see also Chapman, 1964).

Although the results showed that both codends with square-mesh panels were effective in reducing the by-catch of non-target species, the panel was most effective when used in conjunction with a codend of 100 meshes circumference. There were no significant differences in the mean weights or size-compositions of prawns caught in any of the codends (Figs. 2 and 3, and Table 1) indicating that there appears to be little advantage associated with a posterior circumference of 200 meshes in terms of enhancing prawn catches. It may be possible, however, to further enhance the escape of unwanted fish by altering the design of the square-mesh panel. One possibility would be to extend the length of the 40 mm panel to the leading edge of the anterior section, thereby providing a greater area over which fish such as stout whiting may randomly escape. Whilst a concomitant increase in mesh size might further aid the escape of these fish, the size-compositions of stout whiting captured in the 100 panel and 200 panel codends and their respective controls suggests that the size of mesh used in this panel was effective in retaining fish of commercial size (> 16 cm) (Fig. 4). Any increase in the size of mesh may result in the escape of these desirable individuals.

In this study we have shown the potential of a new type of square-mesh panel in significantly reducing by-catch whilst quantifying the effects that codend circumference has on both the selectivity of conventional codends and the escape of fish through panels of square-mesh. In so doing, we have shown very different selectivity characteristics of these codends depending on the way the netting is configured (in both the presence and absence of square-mesh panels). Clearly, it is important to estimate the selectivity parameters of alternative conventional codends (with respect to their circumference, geometry and water flow) so that by-catch-reducing devices like square-mesh panels can be incorporated in the most effective way.

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Fishermen and scientists solving by-catch problems: examples from Australia and possibilities for New England.

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Fishermen and Scientists Solving Bycatch Problems: Examples from Australia and Possibilities for the Northeastern United States

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A framework for solving bycatch problems that involves a pairing of the different areas of expertise of scientists and fishermen is described. Initially, large-scale observer programs are used to identify and quantify bycatches and determine problems without relying on anecdotal information. These involve scientists collecting information at sea from normal commercial fishing operations and are a necessary prerequisite for any attempt to ameliorate bycatch problems. Once the species-specific distributions and abundances of bycatches are determined, manipulative experiments using chartered commercial fishing vessels doing controlled, replicated, paired comparisons are conducted to test gears modified for improved selectivity. For prawn trawl fisheries in Australia, modifications such as the Nordmore grid and square-mesh panels have been found to reduce the unwanted bycatch of small finfish while maintaining catches of prawns and other desired byproduct (slipper lobsters, squid, octopus, etc.). It is vital to involve fishermen in such work so that: (1) they are seen to be the driving force in addressing any conflicts that may come from their bycatches, (2) scientists can fully use industry's unique practical knowledge of the relevant fishing technology, and (3) solutions can be implemented into normal fishing operations quickly and, in some cases, voluntarily. The scientists' role is to organize, analyze, and disseminate the work, provide information on possible solutions through access to the international literature, and to ensure the scientific rigor of the experiments. In New South Wales (NSW), Australia, this framework and its inherent involvement of fishermen has led to a substantial improvement in solving bycatch problems in estuarine and oceanic prawn trawl fisheries. This has been achieved via the voluntary acceptance of modified trawl gears by industry and the consequent publicity. Possibilities for a similar approach to New England's trawl fisheries are discussed.

As predicted some time ago, bycatch has become the fisheries issue of the 1990s (e.g. Klima 1993, Tillman 1993). This is apparent not only from the number and frequency of bycatch conferences, but from the enormous concern and publicity that the issue has attracted from a wide variety of people and interest groups. Recently declining fish stocks in many of the world's fisheries has led to commercial and recreational fishermen, conservationists, environmentalists, politicians, fisheries managers, and scientists all identifying bycatch as a key problem and calling for ways to reduce it. Virtually all fisheries in the world have some bycatch

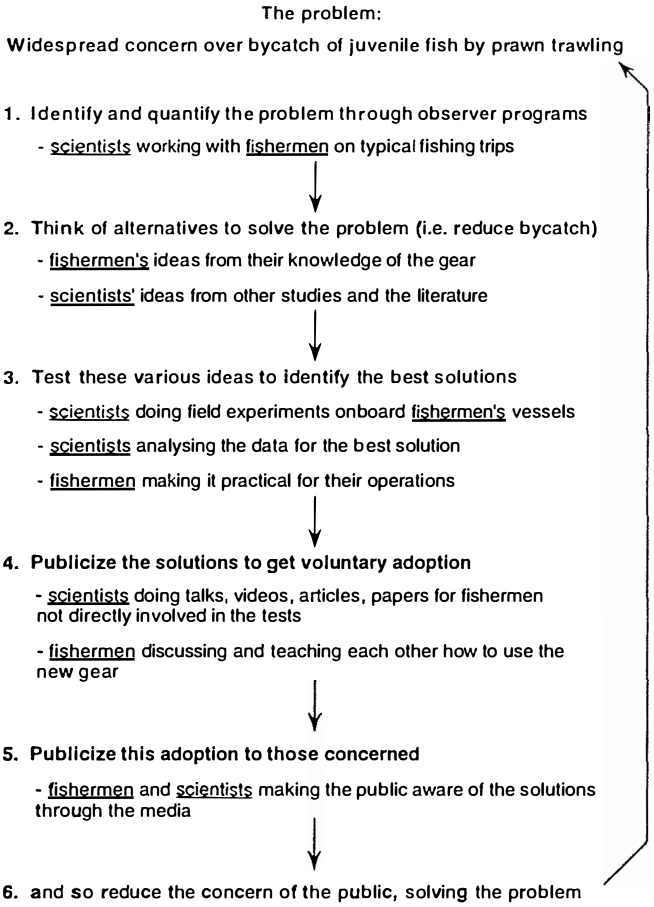

Figure 1. The framework used to address bycatch problems in the estuarine and oceanic prawn trawl fisheries in NSW, Australia.

associated with them, but some types of fishing are recognized as having more bycatch than others; one of the most infamous being shrimp (or prawn) trawling. This type of fishing involves vessels pulling one or more nets made of small mesh over the bottom to catch the quite small, but very valuable, shrimp. Unfortunately, this practice usually results in the capture of most other organisms in the path of the net, and often includes juvenile fish that, when larger, are targeted in other commercial and/or recreational fisheries. This bycatch has led to shrimp trawl fisheries attracting controversy from a variety of sources (in particular other commercial and recreational fishermen) for many years.

In recent years, fishermen and scientists in some parts of the world have successfully solved some of these bycatch problems in shrimp fisheries. In considering the methods used in developing these solutions, it quickly becomes apparent that a relatively simple and logical framework has been used which involves fishermen and scientists each applying their respective areas of expertise to the problem. In general, this framework involves identification and quantification of the relevant issue (via observer programs) and then solving the problem through modifications to commercial fishing gears and/or practices.

In NSW, Australia, we have experienced quite high-profile bycatch problems in our estuarine and oceanic prawn fisheries for many years (as far back as the late 19th century, Dannevig 1904, for review see Kennelly 1995). In the late 1980s these concerns reached a maximum and resulted in threats to close certain prawn fisheries to stop the bycatch of juvenile fish. At this time we discovered that, despite some anecdotal information, there were very little scientific data concerning this problem and so we began our study of this issue by following the framework outlined below.

The Framework Used in NSW

Observer Work

Fig. 1 outlines the logic and framework used to address the problem concerning the bycatch of juvenile fish in NSW's prawn trawl fisheries. The first step (and one of the most vital) was to identify and quantify the problem. This involved determining spatial and temporal variabilities in bycatches at a species-specific level, and could only be done by scientists recording such information onboard commercial vessels during normal fishing operations. Such data could not be collected from information on landings, nor could we rely on fishermen to provide accurate data on discards (it can be argued, in fact, that it is in fishermen's best interests *not* to provide such information). Therefore, the only way to obtain such information was for scientists (and/or scientific observers) to work alongside fishermen on their own vessels and to collect the data in situ by sorting, identifying, measuring, counting, and weighing the catches and bycatches from each tow. We began such an observer program in 1989 by going out on replicated, randomly selected vessels doing typical fishing trips in several estuaries and from several oceanic ports throughout NSW.

During this stage of the work the fishermen and our scientists forged good working relationships that later proved vital in solving the identified bycatch problems. These relationships did not arise out of port meetings, conferences, or workshops (these occurred later), but were developed on the back deck of many different trawlers, at sea, in rivers, during long days and nights, working alongside each other sorting catches from codends. Without working together in such an observer program, we would not have been in a position to solve bycatch problems for two major reasons: (1) we wouldn't have obtained the necessary data on bycatches which identified the particular issues that required solving; and (2) we wouldn't have had the respect from industry that was needed to work with them on solutions.

The data from the observer program led to quite uncompromising information on the bycatches of juvenile fish by the various prawn trawl fleets (Kennelly 1993, Kennelly et al. 1993, Liggins and Kennelly, 1996). For example, in the Clarence River estuarine fishery in 1991-1992, we estimated that in catching 270 t of prawns, this fishery discarded 123 t of bycatch, including approx. 0.8 million individuals of the recreationally important yellowfin bream. In the oceanic fishery offshore from this river in the same year, we estimated that in catching 288 t of prawns, 4,022 t of bycatch was caught (including about 6 million red spot whiting). Of this bycatch, an estimated 725 t was landed for sale as byproduct (including various species of slipper lobsters, squid, octopus and large fish) while the remaining 3,297 t were discarded.

This information was given to fishermen throughout NSW as reports on each fishery and discussed in various meetings. After some debate on the data, these meetings eventually led us and the fishermen to identifying the key bycatch problems in some detail and allowed us to focus on possible solutions. In the above examples, the bycatch and discarding of large numbers of yellowfin bream was clearly seen as a problem for the Clarence River estuarine fishery. For the Clarence River oceanic fishery, the bycatch of large numbers of small red spot whiting and other finfish was seen as a problem but, unlike the estuarine fishery, any solution in this fishery needed to take account of the fishermen's desire to keep certain species of bycatch for sale as byproduct.

Alternative Solutions

Developing alternative modifications to trawl gears to reduce unwanted bycatches in NSW was a joint exercise undertaken by scientists, fishermen, and key net makers. The scientists brought to the table information gleaned from other studies, particularly from the scientific literature, conferences and workshops, and from liaising directly with colleagues throughout the world. The local fishermen and net makers from the Clarence River brought to the table their unique practical knowledge of their fishing gears, vessels, and grounds, and how various modifications may be applied in their operations. In this way we could identify which modifications warranted further consideration and field testing.

Testing the Alternatives

After these discussions, we decided to test several kinds of square mesh panels and Nordmore grids in these estuarine and oceanic fisheries via manipulative experiments onboard chartered commercial vessels set up to trawl in the conventional way. The decision to use commercial vessels rather than research vessels to do this research was important because: (1) it supplied us with a skipper and crew who possessed vital local knowledge of the conventional methods used and the prawn grounds in the test areas, (2) it supplied us with the control gears (conventional nets) against which we tested our modifications, and (3) it ensured the involvement of the rest of the fleet who weren't chartered for the research because it was being done alongside them, in their grounds, using similar gear and vessels. Details of these experiments are found in Broadhurst and Kennelly (1994, 1996), Broadhurst et al. (1996a, 1996b). In general, these experiments took the form of paired comparisons of modified nets with conventional nets and were analyzed using paired t-tests.

After preliminary trials, refinements to various modifications, re-testing, refining again, re-testing, etc., we came up with a few modifications that seemed to work quite well in the two fisheries. Because the targeted eastern school prawns in the estuarine fishery were smaller than the bycatch to be excluded, we concluded that some type of Nordmore grid would be most suitable for this fishery (Fig. 2). For the oceanic fishery, we concluded that such grids were not appropriate because the targeted eastern king prawns were much larger and the grids tended to exclude most of the byproduct species (slipper lobsters, octopus, squid, larger fish, etc.) which the fishermen wished to retain. For this fishery we decided that some form of square mesh panel anterior to the codend might be suitable (Fig. 3); the theory being that small fish could swim out of the codend with the water flowing through the panel while the less mobile prawns, slipper lobsters, squid,

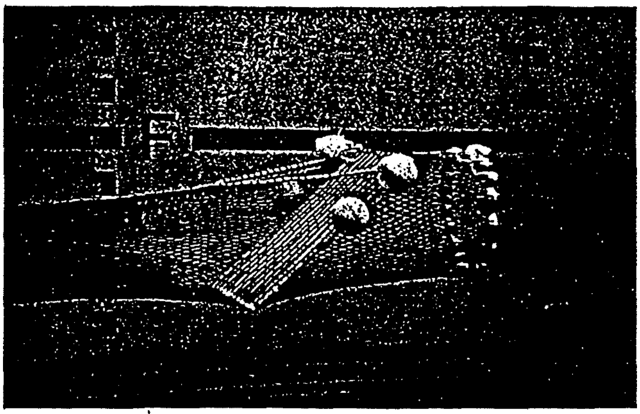

Figure 2. The Nordmore grid design tested in the Clarence River estuarine prawn trawl fishery.

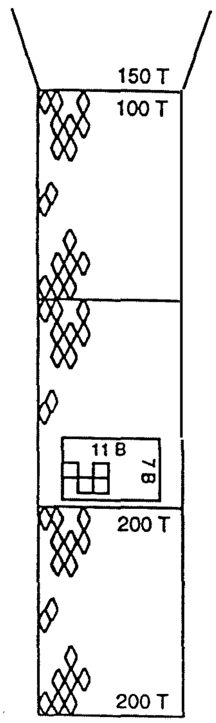

Figure 3. Diagrammatic representation of a modified codend incorporating a square mesh panel as tested in the Clarence River oceanic prawn trawl fishery. T = transversals, B = bars (from Broadhurst et al. 1996b).

and octopus would go to the back of the codend. The sizes of fish excluded in this way could be selected by adjusting the mesh size in the square mesh panel.

Examples of the results from the formal testing of these two alternatives are seen in Figs. 4 and 5. The photographs in Fig. 4 show the striking difference in bycatches that came from using the Nordmore grid in the Clarence River estuary. Similar results occurred from using a simple square mesh panel in the oceanic fishery. The graphs and analyses of the data from these trials (Fig. 5) confirmed the effects seen in the photographs where the modifications greatly reduced bycatches, especially that of the unwanted fish, while maintaining catches of prawns.

Informing Other Fishermen of the Results

While the graphs and analyses of the data from the above trials convinced us and other scientists of the usefulness of the modifications, it was the photographs (e.g. Fig. 4) and videos, and meetings between the scientists and chartered fishermen that illustrated the success of these modifications to fishermen who were not directly involved in the research. We distributed the photographs and videos to fishermen in the relevant ports and encouraged the circulation of the information to other ports. The fishermen involved in the trials discussed the modifications with other fishermen and assisted them in making and using the modifications. These new users then informed other users and before long, the majority of fishermen in the Clarence River estuarine and oceanic fisheries were using these gears and reducing their unwanted bycatches—all on a purely voluntary basis, without any changes in regulations. News of these modifications spread to other fisheries throughout NSW and Queensland, and several fishermen in these other ports are now also using these gears. We are recommending to fisheries managers the legislative adoption of these modifications to ensure 100% compliance in these fisheries. Because of the voluntary acceptance of the new gears, we believe that this last step should be a relatively painless process.

Informing the Public of the Solutions

Unfortunately, the success outlined above of reducing bycatches is insufficient by itself to solve the overall bycatch problem. While this work has gone a long way in nullifying the problem of unwanted bycatch, we haven't yet explained how we

Figure 4. *Two examples of the catches from paired comparisons in the Clarence River estuarine prawn trawl fishery using a conventional codend (on the left) and one with a Nordmore grid (on the right).*

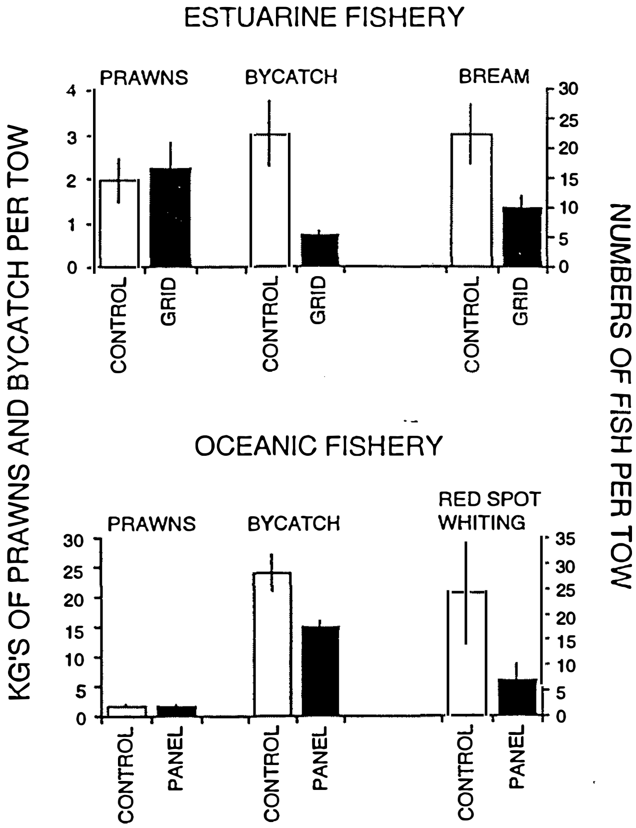

Figure 5. *Summaries of data (for weights of prawns and bycatch and numbers of key fish species) from comparisons of a codend with the Nordmore grid and a conventional codend in the Clarence River estuarine prawn trawl fishery and those from comparisons of a codend with the square mesh panel and a conventional codend in the Clarence River oceanic prawn trawl fishery.*

addressed the public concern over the issue. This could only be done by widespread publicity of the solution, its development, testing, and voluntary acceptance by fishermen to those most concerned with the issue. In our example, this was achieved by the fishermen and ourselves making presentations to committees (representing other commercial and recreational fisheries) and releasing photographs, videos, interviews, etc. to the print, radio and television media. Armed with such evidence (in addition to the publication of the results in scientific journals), we were able to reduce perceived problems concerning this issue in these fisheries. This approach has led to a marked decrease in the conflict associated with bycatch in these fisheries and, in general, a more popular prawn trawl industry in the Clarence River region.

Possibilities for the Northeastern United States

In an effort to apply this approach to similar bycatch problems in a completely different part of the world with very different fisheries, we considered the trawl fisheries of the northeastern United States. In examining these fisheries, we are struck by many similarities in the approach already used by fishermen and scientists to solve bycatch problems. A large observer program has been running in this region's fisheries for the past six years (by Manomet Observatory under contract to the National Marine Fisheries Service) which forms the chief source of information on discards prerequisite to solving perceived problems (Murawski et al. 1995). The data from this program identified problems in the bycatch from the oceanic shrimp fishery in the Gulf of Maine and, after a period of development by scientists and fishermen, a Nordmore grid system is now being used to reduce unwanted bycatches (Kenney et al. 1991, Richards and Hendrickson 1995). While the introduction of these grids into this fishery was not done voluntarily but was mandated, there is now reasonable acceptance of the gear by fishermen.

The groundfish trawl fisheries of the northeastern United States have also attracted their share of attention with regard to their bycatch and subsequent discarding of other species and undersize individuals of target species. Preliminary examination of the observer database for these trawlers from 1990 to 1994 is seen in Fig. 6 which shows the average catch and discard rates per trawl hour of several important species in this region. The data come from groundfish trawlers sampled over a four year period and are arranged according to the various statistical areas where there was sufficient sampling. The data show quite significant discarding rates of the five species shown, but these catch rates depend on the area in question. For example, quite large weights of the commercially and recreationally important lobsters were discarded from trawls done in area 539 (just south of Rhode Island) while in other areas, a lower level of catch was observed with approximately similar weights of lobsters being discarded and retained. The discarding of haddock mainly occurred in areas 561 and 562 (east of Georges Bank) and may have been due to 500 lb. catch limits being placed on the fishery in recent years. Yellowtail flounder appeared in catches throughout New England with fairly high levels of discarding evident. Scup (an important recreational species) was discarded in quite large quantities from trawls done in areas 613 to 622 (from New York to Delaware) and the discarding of small weights of striped bass (another key recreational species) occurred in areas 613 and 621.

The levels of discarding described above clearly suggest some potential problems for these trawlers in terms of their bycatches and is also being manifested as substantial conflicts with other user groups. In particular, the discard of lobsters by trawlers has caused conflict with lobster trappers and the discarding of scup and

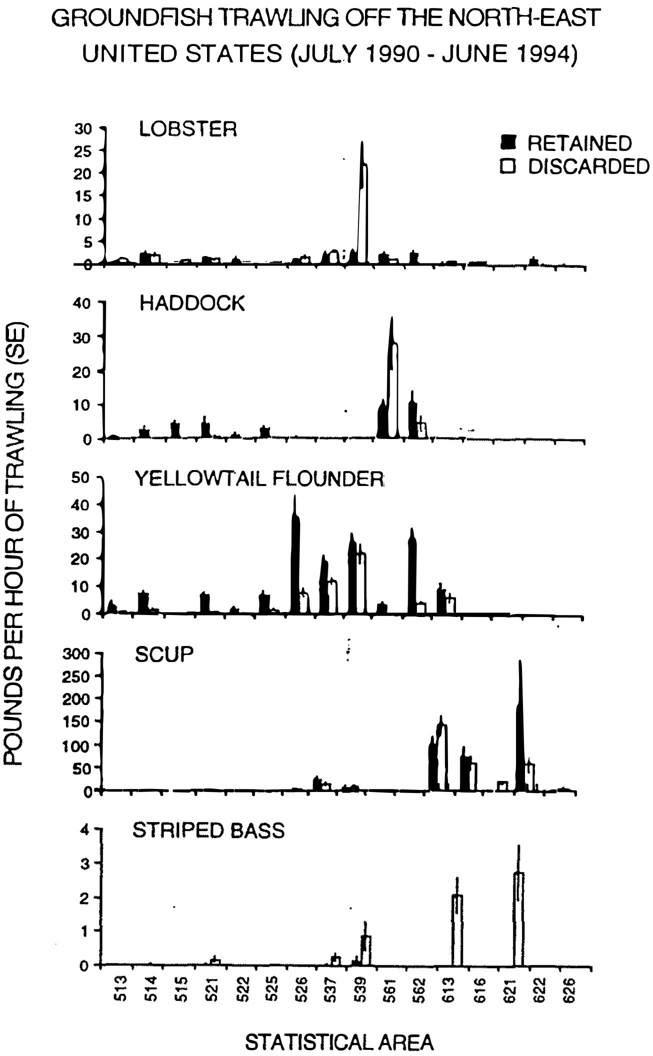

Figure 6. Summaries of observer data from the NMFS northeast sea sampling program.

striped bass has caused some problems with recreational fishing groups.

While the solutions to these problems for fish trawl gear may not be quite as simple as using Nordmore grids or simple square mesh panels in shrimp trawl gear, recent developments in sorting devices for finfish and other species in fish trawl gear may provide some possible solutions. Such modifications as downward sorting grids and horizontal panels in nets have been shown to have great potential for reducing the bycatches of unwanted species and unwanted sizes of certain species in groundfish trawls (Fig. 7, Isaksen 1994, Engas and West 1995). Together with scientists from the Marine Laboratory in Aberdeen, Scotland, Institute of Marine Research in Norway, the

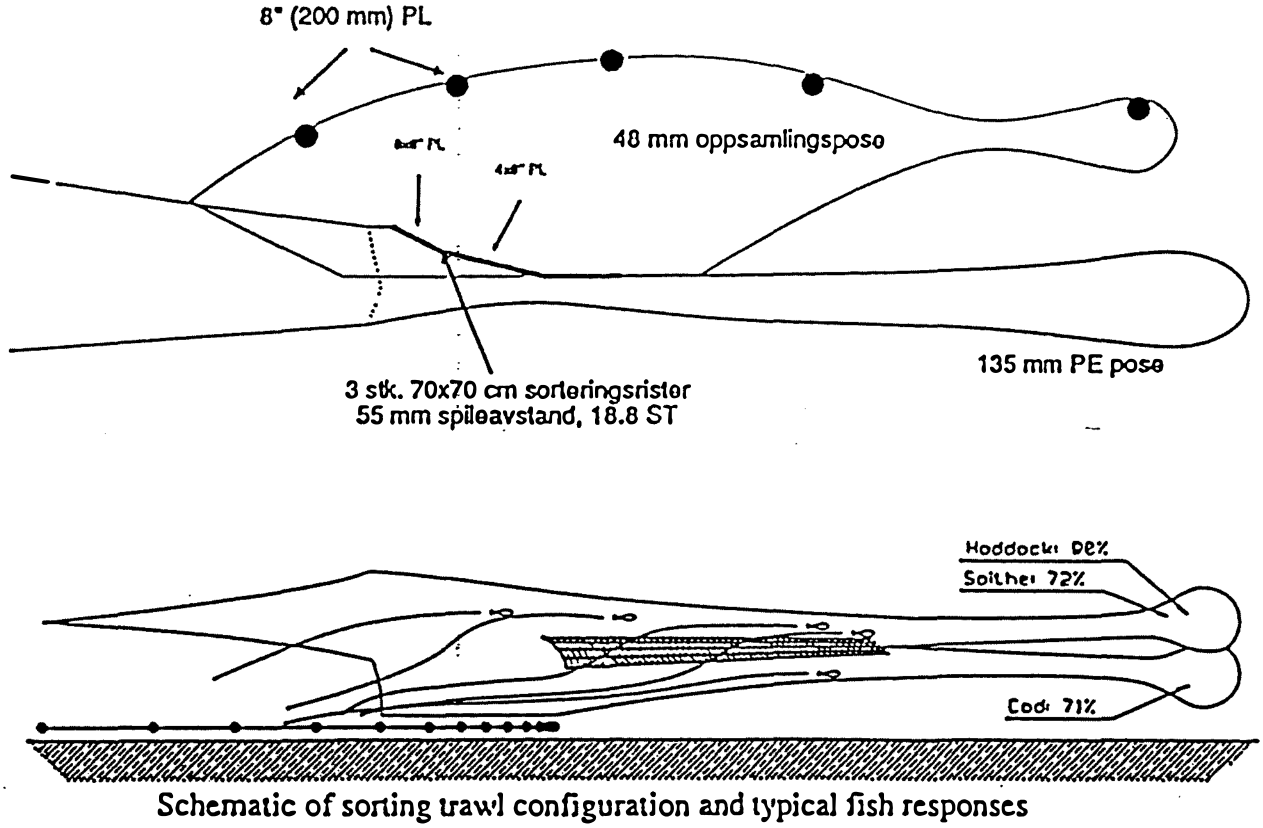

Figure 7. A finfish sorting grid (from Isaksen 1993, top) and a horizontal sorting device (from Engas and West 1995, bottom) being tested in Norway to separate different species and sizes of groundfish.

Massachusetts Division of Marine Fisheries, and local fishermen, we plan to test the effectiveness of some of these designs in the groundfish trawl fisheries off the northeastern United States in the near future. Because of the existence of the large-scale, long term observer program, the most difficult job in solving such bycatch problems is already in hand: (1) we already have good observer data that identifies and quantifies the problems and, more important, (2) we have established a working environment with fishermen that hopefully will enable such solutions to be found and eventually adopted.

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Rigid and flexible separator-panels in trawls that reduce the by-catch of small fish in the Clarence River prawn-trawl fishery, Australia.

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Mar. Freshwater Res., 1996, 47, 991–8

Rigid and Flexible Separator Panels in Trawls that Reduce the By-catch of Small Fish in the Clarence River Prawn-trawl Fishery, Australia

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Abstract. Two experiments were done in the Clarence River prawn-trawl fishery that compared catches and by-catches from conventional trawls with those from modified trawls containing rigid and flexible separator panels. The modifications included *(1)* a soft separator panel, the 'blubber-chute' (used commercially by fishers to exclude jellyfish), *(2)* the standard Nordmøre grid, containing a guiding panel, and *(3)* a modified Nordmøre grid that had no guiding panel but included a flexible cover of mesh lying semi-attached over the escape exit. In the first experiment, simultaneous paired comparisons among these designs and their controls showed that although all three modified trawls significantly reduced the by-catch of small fish by between 75% and 90%, the standard Nordmøre grid was the only design that did not significantly reduce catches of prawns. In the second experiment, which compared this standard grid with the control during a period of flooding when the by-catch of non-target species was quite high, the standard grid significantly reduced the by-catch of juvenile bream (*Acanthopagrus australis*) (by 67%) with no significant reduction in catches of prawns. The potential for the Nordmøre grid to alleviate deleterious effects of prawn trawling in estuaries is discussed.

Introduction

Estuarine trawling for prawns occurs in five localities in New South Wales (NSW) and is valued at approximately \$A7 million per annum (1990–91) (Pease and Scribner 1993). As with most prawn-trawl fisheries, significant numbers of non-targeted organisms, or by-catch, are captured incidentally with the targeted prawns (for reviews, see Saila 1983; Andrew and Pepperell 1992; Kennelly 1995). A recent three-year observer-based study that quantified the distributions and abundances of the key by-catch species throughout the prawn-trawl fisheries of NSW showed that despite large spatial and temporal variabilities in the by-catches of many species, some juveniles of commercially and recreationally important species were caught in large numbers throughout entire trawling seasons (Kennelly 1993). In particular, prawn trawlers working in the Clarence River (Fig. 1) from October to May each year had mean estimated by-catches of up to 829000 bream (*Acanthopagrus australis*), 286000 sand whiting (*Sillago ciliata*), 122000 tailor (*Pomatomus saltator*) and large numbers of several non-commercial species (Liggins and Kennelly 1996).

The mortality of large numbers of these individuals raised concerns over the potential negative impacts of prawn trawling in this estuary on the recruitment, biomass and yield of stocks that form the basis of other target fisheries. These concerns resulted in the current investigation, which examines various modifications to trawls and trawling practices that minimize undesirable by-catches while maintaining catches of prawns.

Several trawl fisheries throughout the world have alleviated problems of by-catch by modifying trawls to incorporate by-catch reduction devices (BRDs) (Christian and Harrington 1987; Averill 1989; Kendall 1990; Isaksen *et al.* 1992; Rulifson *et al.* 1992). These studies have shown that the application of such modifications must be specific to individual fisheries and depends on several factors, including the species to be excluded, the extent to which their behaviour is understood, the size of nets, methods of handling, and the location and type of trawl grounds. For example, because of the behavioural differences between some species of fish and prawns, it is possible to exclude small and/or fusiform species by using strategically placed escape windows (e.g. Watson *et al.* 1986; Matsuoka and Kan 1991; Broadhurst and Kennelly 1994, 1995). Alternatively, fisheries that seek to remove larger individuals from trawls, by physical separation, may incorporate some form of separator panel located anterior to the codend (e.g. Christian and Harrington 1987; Kendall 1990; Isaksen *et al.* 1992; Broadhurst *et al.* 1996). Such a panel may be made of flexible netting or a rigid grid. Although it is possible that several designs of BRDs may meet the specific criteria for any given fishery (including the ability to remove by-catch and maintain catches of target species), their ultimate acceptance by industry is determined by the extent to which they influence normal commercial operations (i.e. setting and retrieval of gears; see also Kendall 1990).

BRDs are usually introduced to trawl fisheries as an input control to reduce the potential negative impacts associated with trawling and consequent conflict between different user groups (Watson *et al.* 1986; Kendall 1990; Rulifson *et al.* 1992). In some fisheries, however, they are an essential component of the trawl, used to remove organisms that would otherwise restrict trawling. For example, Clarence

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River prawn trawlers routinely use a BRD designed specifically to exclude jellyfish (*Catostylus* sp., which occurs in large densities at certain times and locations in the river). Commonly called 'blubber-chutes', these BRDs consist of a funnel of soft mesh inserted into the aft belly of the trawl. Organisms larger than the mesh in the blubber-chute are forced through an opening in the top of the trawl while prawns and smaller individuals pass through the blubber-chute mesh and into the codend. Evidence from the observer study suggested that this design of BRD may be effective in excluding some fish from the trawl, depending upon the size of mesh used (see Kennelly *et al.* 1992).

Because the individuals comprising by-catch in the Clarence River are predominantly larger than the targeted prawns, separator panels that mechanically partition the catch may eliminate a large proportion of the by-catch in this fishery. A previous experiment examining the performance of several designs of modified codends (Broadhurst *et al.* 1996) showed that a rigid separator panel, termed the Nordmøre grid, significantly reduced the mean weight of by-catch by 77% with no effect on the catches of prawns; the rigid structure and fixed bar spacings of this design provided accurate size separation of individuals and we recommended that further research be done to develop this design for commercial application in the Clarence River. Of particular importance was to determine its performance across a range of conditions—especially during periods of flooding in the river over summer when catches and by-catches are much greater than at other times.

To promote the acceptance of the Nordmøre grid in this fishery and to quantify the performance of the commercially used blubber-chute in reducing the by-catch of small fish, the aims of the present study were *(i)* to assess the performance of two variations of the Nordmøre grid and the blubber-chute in reducing by-catch in the Clarence River prawn-trawl fishery under normal commercial conditions, and *(ii)* to test the most appropriate design during a period of flooding in the river when the by-catch of fish is usually greater than at other times.

Materials and Methods

Two experiments were done, one each in Lake Wooloweyah and the Clarence River (Fig. 1) in January and February 1995, using a commercial prawn trawler (10 m) on established trawl grounds. Two florida flyer nets (mesh size 40 mm), 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 2·5 kn. Both nets were rigged with zippers to facilitate changing of the codends (see Broadhurst *et al.* 1996).

Experiment No. 1: Comparison of Three BRDs

Three designs of BRDs and a control codend were constructed. The first design (the blubber-chute) had a panel of netting (mesh size 85 mm) sewn into a funnel (with an anterior circumference of 60 meshes) and attached to the body of the net at the point where the net was 240 meshes in circumference (Fig. 2). The posterior point of this panel was attached 20 meshes from the end of the codend. A 24-mesh-long opening (termed the escape exit) was cut in the codend immediately anterior to this point of attachment. The second and third designs (termed the standard and modified Nordmøre grids, respectively) comprised identical aluminium grids scaled to fit the net (Fig. 3; see also Isaksen *et al.* 1992). The standard Nordmøre grid was constructed with a guiding panel (40-mm mesh) (Fig. 4*a*) that directed the catch to the bottom of the grid. The modified Nordmøre grid had no guiding panel but included a flexible cover of 40-mm mesh hung loosely over the escape exit (Fig. 4*b*). This mesh was attached to the net only anteriorly and was free to lift open over the escape exit. We hypothesized that this modification would prevent prawns from escaping but still allow organisms larger than the bar spacings to escape from the trawl. The control codend was constructed from the same netting materials as those described above, but it included no BRD and had net extensions added to maintain the same length of trawl as each of the respective BRDs.

All three designs were compared against each other and against their respective controls, with one of each being paired on each side of the twin-rigged gear (i.e. six separate paired comparisons). During eight days in the trawling season in Lake Wooloweyah, 15 replicate 30-min tows were completed for each paired comparison. The location of each tow was randomly selected from the available prawn-trawl locations that were possible under the particular conditions. Prior to the trials, each net was rigged with normal commercial codends to test that there were no differences in the fishing characteristics of each net. The position and order

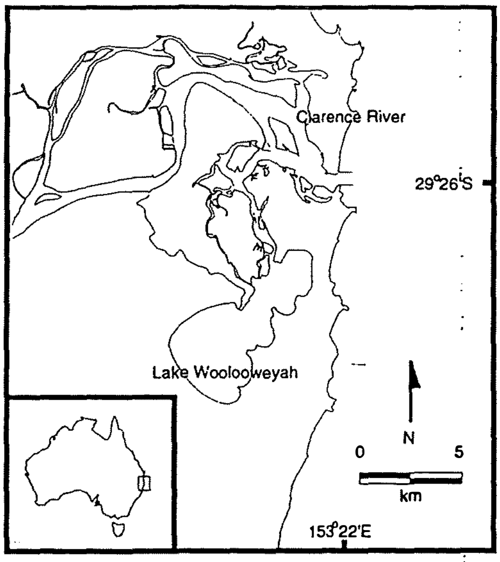

Fig. 1. Clarence River and Lake Wooloweyah.

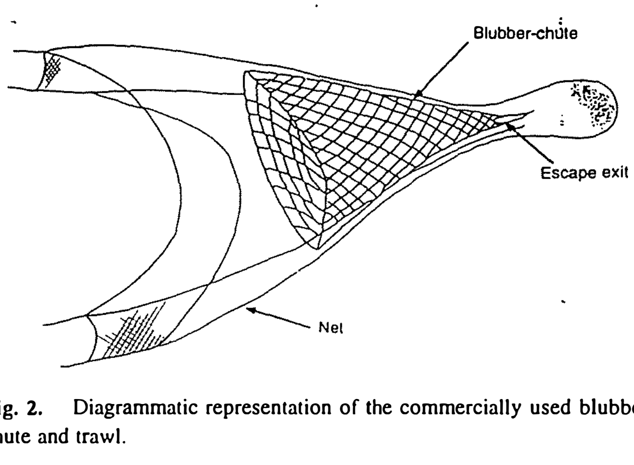

Fig. 2. Diagrammatic representation of the commercially used blubber-chute and trawl.

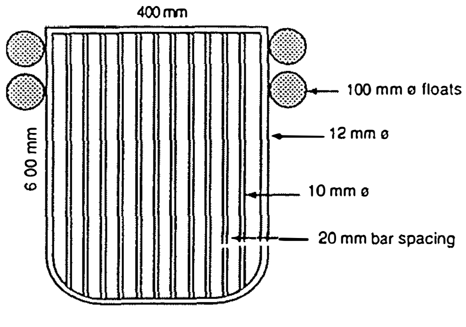

Fig. 3. Aluminium grid used in the standard and modified Nordmøre grids.

of the two Nordmøre grid designs was randomly determined. However, because the blubber-chute could not be easily removed from the net, all paired comparisons associated with this design involved alternating the blubber-chute between nets on different days.

Experiment No. 2: Testing of a Standard Nordmøre Grid during a Flood

In this experiment, the standard Nordmøre grid from Experiment No. 1 was tested against its control during a period of flood in the Clarence River when it was anticipated that amounts of by-catch would be large. The position and order of each codend was randomly determined and used in normal commercial tows of 30 min duration. Over three days, 14 replicate paired comparisons were completed.

Data Collected from the Experiments

After each tow in each experiment, the codends were emptied onto a partitioned tray. All organisms were sorted according to species. Data collected from each tow were: the total weight of prawns, the total weight of by-catch, the weights, numbers and sizes of commercially and/or recreationally important species (to the nearest 0·5 cm), the numbers of non-commercial and/or non-recreational species, and the total numbers of non-commercial species in the assemblage. All prawns in a subsample of the total prawn catch from each tow (50 prawns from each net) were measured in the laboratory (to the nearest 1 mm carapace length). Several species were caught in sufficient quantities to provide meaningful analyses. These were eastern king prawns (*Penaeus plebejus*), school prawns (*Metapenaeus macleayi*), bream (*Acanthopagrus australis*), blue swimmer crabs (*Portunus pelagicus*), tarwhine (*Rhabdosargus sarba*), tailor (*Pomatomus saltator*), southern herring (*Harengula abbreviata*), pink-breasted siphon fish (*Siphamia roseigaster*), silver biddies (*Gerres subfasciatus*), trumpeter (*Pelates quadrilineatus*) and catfish (*Euristhmus lepturus*).

Data from all replicates that had sufficient numbers of each variable (i.e. >2 fish) for the paired comparisons between the BRDs and their controls were analysed in one-tailed paired *t*-tests (testing the hypothesis that the BRDs caught less than their controls), whereas the paired comparisons between the various BRDs were analysed in two-tailed paired *t*-tests. Size frequencies of prawns and bream were plotted and compared by two-sample Kolmogorov–Smirnov tests ($P = 0.05$).

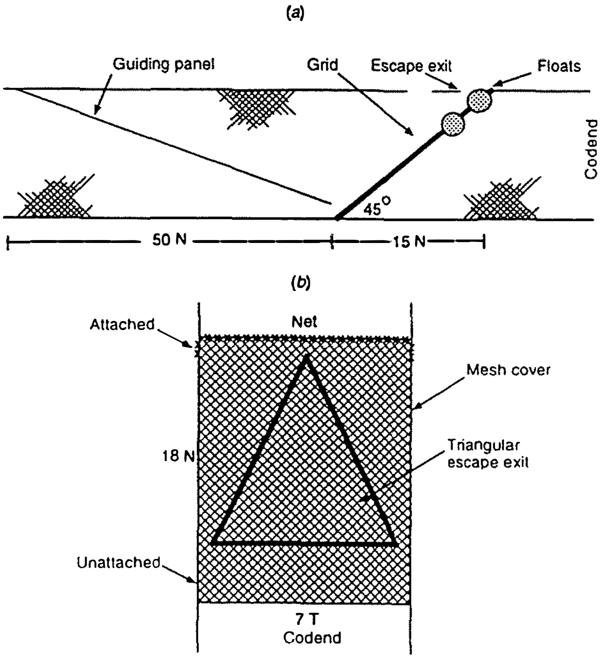

Fig. 4. Diagrammatic representation of *(a)* the standard Nordmøre grid (side view) and *(b)* the mesh cover over the escape exit in the modified Nordmøre grid (top view). T, transversals; N, normals.

Results

Experiment No. 1: Comparison of Three BRDs

Compared with their respective controls, the blubber-chute and the standard and modified Nordmøre grids all significantly reduced the weights of total by-catch (by 75%, 90% and 81·9%, respectively), the numbers and weights of blue swimmer crabs, and the numbers of southern herring and trumpeter (Figs 5*b*, 5*c*, 5*f* and 5*h*; Table 1). The blubber-chute significantly reduced the numbers of tarwhine (Fig. 5*d*; Table 1), both the blubber-chute and the modified Nordmøre grid significantly reduced the numbers of tailor (Fig. 5*e*; Table 1) (there were insufficient tailor from the standard Nordmøre grid to enable statistical analyses), and the standard Nordmøre grid reduced the numbers of non-commercial species (Fig. 5*i*; Table 1). The standard Nordmøre grid showed no significant reduction in the mean catches of prawns, whereas the blubber-chute and the modified Nordmøre grid caught significantly fewer prawns than did their controls (means reduced by 13% and 11·5%, respectively) (Fig. 5*a*; Table 1).

There were no significant differences between the blubber-chute and the modified Nordmøre grid for any of the variables tested (Fig. 5; Table 1). Compared with the other designs, the standard Nordmøre grid caught significantly less by-catch and fewer non-commercial species (Figs 5*b* and 5*i*; Table 1). The standard Nordmøre grid also caught significantly more prawns than the blubber-chute (Fig. 5*a*; Table 1).

Two-sample Kolmogorov–Smirnov tests comparing the size–frequency compositions of school prawns measured from each sample showed that the modified Nordmøre grid retained proportionally fewer large school prawns than did its control (Fig. 6*a*). The blubber-chute and the standard Nordmøre grid retained proportionally fewer large king prawns than did their respective controls (Figs 6*b* and 6*c*). The modified Nordmøre grid retained proportionally fewer

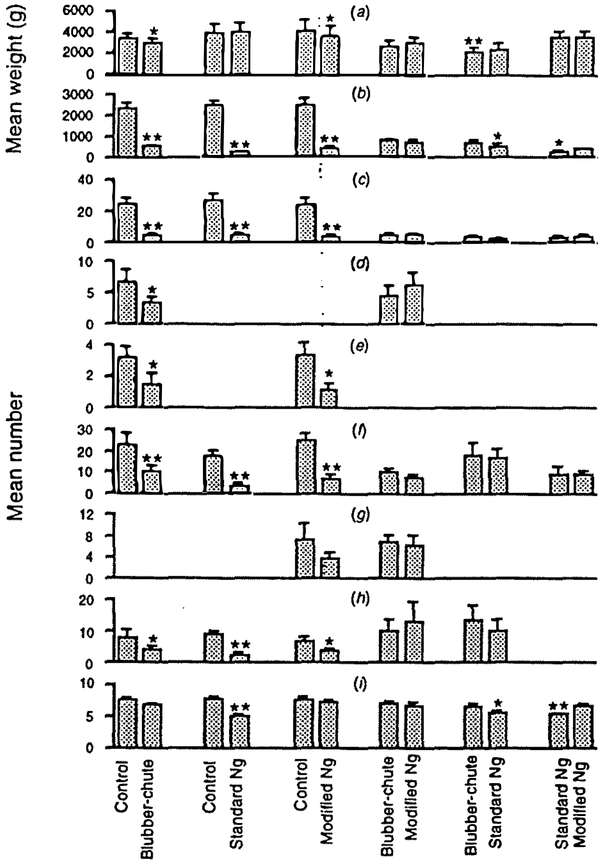

Fig. 5. Differences in mean catches (per 30-min tow; + s.e.) between the various modified codends and controls: weights of *(a)* prawns and *(b)* total by-catch; numbers of *(c)* blue swimmer crabs, *(d)* tarwhine, *(e)* tailor, *(f)* southern herring, *(g)* silver biddies, *(h)* trumpeter and *(i)* non-commercial species. Significance: $^{**}P < 0.01$; $^{*}P < 0.05$. Ng, Nordmøre grid.

large king prawns than did the standard Nordmøre grid and proportionally fewer small king prawns than the blubber-chute (Figs 6*d* and 6*e*).

Experiment No. 2: Testing of a Standard Nordmøre Grid during a Flood

During a period of flooding in the Clarence River, the standard Nordmøre grid significantly reduced the weights of total by-catch (mean weight reduced by 76%), the numbers and weights of bream (means reduced by 67% and 88%, respectively), and the numbers of southern herring (by 73%), catfish (by 37%) and non-commercial species (Figs 7*b*–7*e*; Table 2). This design had no significant effect on the weights of prawns, although the mean catch was 10% lower than that of the control (Fig. 7*a*; Table 2).

Two-sample Kolmogorov–Smirnov tests comparing the size–frequency distributions for bream and school prawns showed that the standard Nordmøre grid caught proportionally fewer large bream and fewer small- to medium-sized school prawns than did the control (Figs 8*a* and 8*b*).

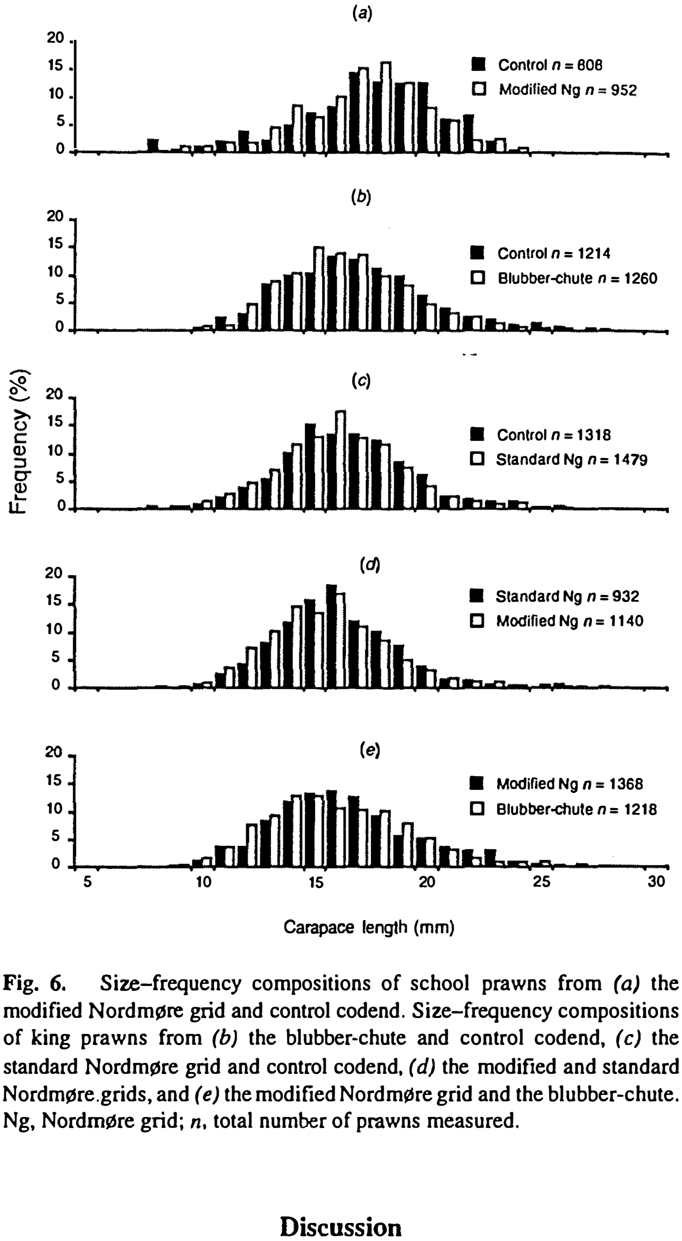

Fig. 6. Size–frequency compositions of school prawns from *(a)* the modified Nordmøre grid and control codend. Size–frequency compositions of king prawns from *(b)* the blubber-chute and control codend, *(c)* the standard Nordmøre grid and control codend, *(d)* the modified and standard Nordmøre grids, and *(e)* the modified Nordmøre grid and the blubber-chute. Ng, Nordmøre grid; *n*, total number of prawns measured.

Discussion

As in other papers (Kendall 1990; Isaksen *et al.* 1992), the results from this study have quantified the degree to which trawls with separator panels reduce the by-catch of non-target species. By testing the blubber-chute and the two variations of the Nordmøre grid against their respective controls and each other, the present study also showed the relative effectiveness of each of these designs in reducing the by-catch of small fish while maintaining catches of prawns under normal commercial conditions.

Although all three designs tested in Experiment No. 1 significantly reduced total by-catch (means reduced by between 75% and 90%) and the numbers of small fish such as trumpeter and southern herring, the standard Nordmøre grid was the only design that did not significantly reduce catches of prawns (see also Isaksen *et al.* 1992). Compared with the other designs, this BRD also caught significantly

Table 1. Summaries of one-tailed paired t-tests comparing BRDs against their controls and two-tailed paired t-tests comparing BRDs against each other in Experiment No. 1
Ng, Nordmøre grid; n, number of replicates; $^{**}P < 0{\cdot}01$; $^{*}P < 0{\cdot}05$

	Blubber-chute *v.* control (one-tailed)		Standard Ng *v.* control (one-tailed)		Modified Ng *v.* control (one-tailed)		Blubber-chute *v.* modified Ng (two-tailed)		Blubber-chute *v.* standard Ng (two-tailed)		Standard Ng *v.* modified Ng (two-tailed)	
	P	*n*	*P*	*n*	*P*	*n*	*P*	*n*	*P*	*n*	*P*	*n*
Wt of prawns	0·017*	15	0·724	15	0·020*	15	0·088	15	0·006**	15	0·953	15
Wt of total by-catch	0·0001**	15	0·0001**	15	0·0001**	15	0·504	15	0·025*	15	0·027*	15
Commercial by-catch												
Wt of blue swimmer crabs	0·0001**	15	0·0001**	15	0·0001**	15	0·154	13	0·061	12	0·127	10
No. of blue swimmer crabs	0·0001**	15	0·0001**	15	0·0002**	15	0·842	13	0·140	12	0·417	10
No. of tarwhine	0·032*	10	—	—	—	—	0·508	11	—	—	—	—
No. of tailor	0·040*	10	—	—	0·020*	10	—	—	—	—	—	—
Non-commercial by-catch												
No. of southern herring	0·001**	15	0·0001**	14	0·0001**	15	0·072	15	0·652	15	0·984	14
No. of pink-breasted siphon fish	0·323	14	0·725	15	0·089	15	0·121	15	0·474	14	0·121	15
No. of silver biddies	—	—	—	—	0·138	11	0·076	14	—	—	—	—
No. of trumpeter	0·040*	13	0·0001**	12	0·049*	13	0·342	14	0·412	10	—	—
No. of non-commercial species	0·091	15	0·0001**	15	0·212	15	0·731	15	0·041*	15	0·0002**	15

Table 2. Summaries of one-tailed paired t-tests comparing the standard Nordmøre-grid and the control during a flood in experiment No. 2.
Ng, Nordmøre-grid; n, number of replicates; $^{**}P<0{\cdot}01$; $^{*}P<0{\cdot}05$

	Standard Ng *v.* Control	
	P	*n*
Wt of prawns	0·068	14
Wt of total by-catch	0·0002**	14
Commercial by-catch		
Wt of bream	0·004**	12
No. of bream	0·011*	12
Non-commercial by-catch		
No. of southern herring	0·005**	13
No. of catfish	0·007**	14
No. of non-commercial sp	0·003**	14

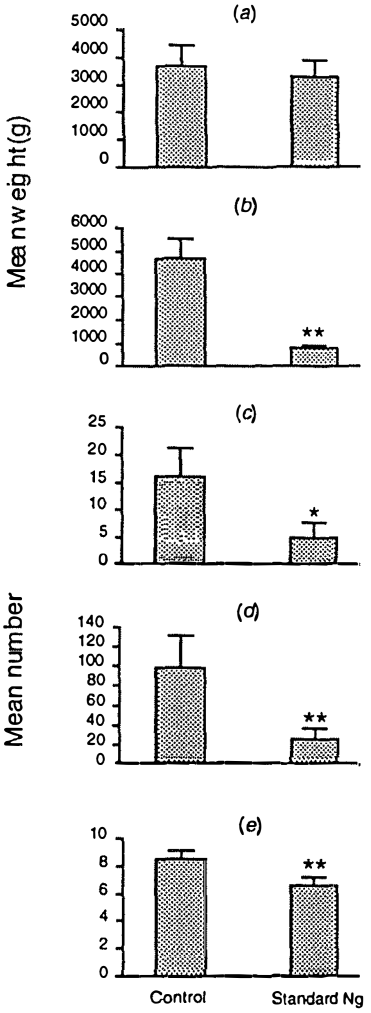

Fig. 7. Differences in mean catches (per 30-min tow; + s.e.) between the standard Nordmøre grid and its control during a flood: weights of *(a)* prawns and *(b)* total by-catch; numbers of *(c)* bream, *(d)* southern herring and *(e)* non-commercial species. Significance: $**P < 0{\cdot}01$; $*P < 0{\cdot}05$. Ng, Nordmøre grid.

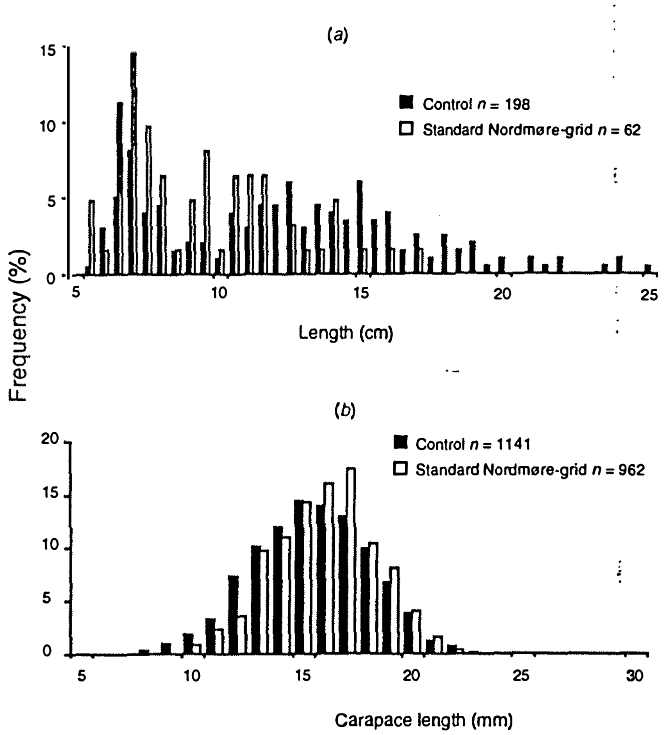

Fig. 8. Size-frequency distributions of *(a)* bream and *(b)* school prawns from the standard Nordmøre grid and control codend tested in Experiment No. 2. *n*, total number of fish or prawns measured.

less by-catch and more prawns than the blubber-chute. These results support those from a previous experiment (Broadhurst *et al.* 1996) that assessed the performance of a design similar to the standard Nordmøre grid tested here (incorporating a guiding funnel instead of a guiding panel) and two BRDs with soft separator panels. In that paper it was concluded that, in addition to its prawn-retention characteristics, there were two reasons why the standard Nordmøre grid appeared to have the most potential for application in the Clarence River: firstly, the grid provided accurate size separation of individual species, increasing the likelihood of excluding individuals larger than a specified size, and secondly, the rigid shape and smooth contours of the grid appeared to exclude seaweed and debris more effectively.

At the end of each tow during Experiment No. 1 in Lake Woolooweyah, the standard Nordmøre grid was observed to be relatively free of seaweed, whereas the blubber-chute and the modified Nordmøre grid often had large quantities entangled between their meshes and bars respectively. This probably decreased the lateral openings between the meshes and bars and contributed towards the escape of prawns from these BRDs. A possible explanation why the standard Nordmøre grid caught less seaweed and consequently more prawns is that the geometric angle and contours of the guiding panel rolled the seaweed into a ball before it reached the grid, facilitating its movement out through the escape hole.

The significant differences between the BRDs in the size compositions of king prawns captured during Experiment No. 1 (Fig. 6) suggest that some large king prawns may have escaped through the BRDs, possibly owing to the effects of the large quantities of weed encountered during the tows (see above). Alternatively, these differences may be attributable to the different behaviours of king and school prawns. In a previous experiment (Broadhurst *et al.* 1996), when the codends were emptied onto the sorting tray king prawns appeared to be more active than school prawns, jumping and 'flipping' for up to a minute. It is possible that the king prawns captured during the present study were more active than school prawns in the trawl, to the extent that some large individuals were able to 'flip' through the escape exits of the various BRDs.

The results from Experiment No. 2 showed that during a flood in the Clarence River, the standard Nordmøre grid was effective in significantly reducing the weights of by-catch (mean weight reduced by 76%) and the numbers of small bream (by 67%) but, although not statistically significant, there was also a concomitant reduction in the catch of prawns (10% reduction in means; Fig. 8*b*). These results are comparable to those detected by Isaksen *et al.* (1992) in the Barents Sea, where the reduction of juveniles of individual by-catch species was around 50% with an associated prawn loss of 2–5%. The escape of the prawns from the grid during Experiment No. 2 in the present study may be explained by *(i)* the partial blocking of the grid due to the large quantities of debris (sticks and logs), rubbish (plastic bags) and larger organisms encountered during the tows (Broadhurst, personal observations), or *(ii)* the continual impact of this debris stretching the meshes surrounding the grid frame and reducing the grid angle to less than 45% (see also Isaksen *et al.* 1992). Although there is little that can be done to prevent debris and rubbish from entering the trawl, use of a netting of heavier ply may strengthen the position of the grid within the trawl and help maintain the correct angle.

These two experiments showed that rigid and flexible separator panels (and especially the standard Nordmøre grid) significantly reduced the by-catch of juveniles of commercially important species in the Clarence River and therefore may provide a way to reduce some of the impacts that prawn trawling may have on subsequent stocks of by-catch species in this fishery. For example, Liggins and Kennelly (1996) estimated that 829000 bream (mean catch) were captured by prawn trawlers working without BRDs in the Clarence River during the 1991–92 season. Combining this figure with R. West's (personal communication) estimate of instantaneous natural mortality ($M = 0{\cdot}3$), their age at legal size (5 years) and the assumption that all the bream died as a result of capture, we calculated that these 829000 bream caught in 1991–92 may have reduced the total number of bream available to other commercial and recreational fisheries five years later by about 185000 fish. If, however, all vessels had been fitted with standard Nordmøre grids, this figure might have been reduced by 67% to about 61000 fish, providing some 124000 additional fish to these other fisheries. In the absence of reliable estimates of natural mortality and the numbers of fish surviving after trawling, such figures will, of course, be questionable, but these calculations nevertheless illustrate that the widespread use of designs like the Nordmøre grid may increase the availability of species such as bream to other commercial and recreational fisheries.

The experiments described in this study have resulted in the use of Nordmøre grids by the majority of Clarence River trawlers on a voluntary basis, in preference to the blubber-chute. These fishers concluded that, although the grid requires slightly more effort and skill in construction and deployment, the characteristics discussed above and the potential for increased trawling time compensate for any additional effort.

Acknowledgments

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Evaluations of the Nordmøre-grid and secondary by-catch reducing devices (BRDs) in the Hunter River prawn-trawl fishery, Australia.

Broadhurst, M.K., Kennelly, S.J., Watson, J. and Workman, I., 1997.

US Fishery Bulletin, Vol. 95, pp. 209-218.

Evaluations of the Nordmøre grid and secondary bycatch-reducing devices (BRD's) in the Hunter River prawn-trawl fishery, Australia

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Abstract.—Several bycatch-reducing devices (BRD's) were compared for their effectiveness in reducing bycatch while maintaining catches of prawns in an estuarine prawn-trawl fishery in New South Wales (NSW), Australia. A solid separator-panel (the Nordmøre grid), a soft separator panel (the commercially used blubber chute), and four secondary BRD's (the fisheye, extended mesh funnel, Allerio Brothers grid, and square-mesh panel) each attached to a Nordmøre grid, were compared against each other in a series of paired comparisons in the Hunter River prawn-trawl fishery. The results showed that the Nordmøre grid and all secondary BRD's caught less bycatch and more prawns than the commercially used blubber chute. Most bycatch seemed to escape with use of the Nordmøre grid, and there was no significant advantage in adding a secondary BRD to this design. The efficiency of the Nordmøre grid has led to its voluntary adoption by many commercial prawn-trawl fishermen throughout NSW estuaries.

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Fishery Bulletin 95:209–218 (1997).

In New South Wales (NSW), Australia, estuarine prawn-trawling occurs in five localities and is valued at approximately A$7 million per annum. Like the majority of the world's prawn-trawl fisheries, significant numbers of nontarget organisms, or bycatch, are captured incidentally with targeted prawns (for reviews see Saila, 1983; Andrew and Pepperell, 1992; Alverson et al., 1994; Kennelly, 1995).

In recent years, bycatch from these fisheries has become of increasing concern to a broad cross section of the fisheries community. As a result, a 3-yr observer-based study was undertaken from 1990 to 1992 to quantify the distributions and abundances of bycatch species (Liggins and Kennelly, 1996; Kennelly[1]). The results from these studies showed that, despite large spatial and temporal variabilities in the bycatches of many species, some juveniles of commercially and recreationally important species were caught in large numbers throughout the trawling seasons. The quantities involved raised concerns over the potential impacts of prawn-trawling on subsequent stocks of these species. These concerns led to the current investigation, which examines various modifications to trawling gear and trawling practices that minimize undesirable bycatches while maintaining catches of prawns.

A number of recent attempts to exclude bycatch from prawn-trawls have concentrated on modifications that incorporate bycatch-reducing devices (BRD's) (Christian and Harrington, 1987; Averill, 1989; Kendall, 1990; Isaksen et al., 1992; Rulifson et al., 1992; Broadhurst et al., 1996). In previous experiments (Broadhurst and Kennelly, 1994, 1995, 1996; Broadhurst et al., 1996) we showed that the successful application of various BRD's is specific to individual fisheries and depends upon several factors, including the type of species to be excluded. Further, to promote acceptance by industry, BRD's should be designed so that they do not adversely influence normal commercial operations.

[1] Kennelly, S. J. 1993. Study of the bycatch of the NSW east coast trawl fishery. Final rep. to the Fisheries Research and Development Cooperation. Project 88/108, ISBN 0 7310 2096 0, 520 p.

In estuarine prawn-trawl fisheries in NSW, many of the individual fish in bycatch are larger than the targeted prawns and include organisms such as jellyfish or jelly "blubber"—*Catostylus* spp. For the past 30 years, many of the estuarine prawn-trawlers in NSW have routinely used a BRD designed specifically to exclude these individuals. Commonly called "blubber-chutes," these BRD's consist of a funnel of soft mesh inserted into the aft belly of the trawl. Organisms larger than the mesh in the funnel are guided through an opening in the top of the trawl, while prawns and smaller individuals pass through the mesh into the codend (see Broadhurst and Kennelly, 1996). In the Hunter River (HR) prawn-trawl fishery (Fig. 1), the abundance of jellyfish means that commercial fishermen use blubber chutes throughout most of the trawling season.

In a series of experiments that examined the performance of several types of BRD's (Broadhurst et al., 1996; Broadhurst and Kennelly, 1996), we showed that a rigid separator-panel (the Nordmøre grid) significantly reduced the mean weight of bycatch in two estuaries and had no effect on the catches of prawns. Compared with the commercially used blubber chute, the Nordmøre grid also retained significantly less bycatch but caught more prawns.

Bycatch-reducing devices, such as the Nordmøre grid and the blubber chute, function by mechanically partitioning the catch according to size (see Broadhurst et al., 1996), and therefore are generally not as effective in excluding unwanted individuals that are of a similar size or that are smaller than the targeted prawns. Previous studies have shown, however, that it may be possible to exclude these smaller individuals by exploiting behavioral differences between some species of fish and prawns (Watson et al., 1986; Broadhurst and Kennelly, 1994, 1995; Broadhurst et al., 1996). For example, studies by Watson et al. (1993) in the Gulf of Mexico showed that small individuals of red snapper (*Lutjanus campechanus*), Atlantic croaker (*Micropogon undulatus*), Atlantic bumper (*Chloroscombrus chrysurus*) and whiting (*Menticirrhus* sp.) were passively excluded from trawls by various BRD designs comprising strategically placed panels of netting and escape exits. These designs were located posteriorly to a larger mechanical separating grid (designed to exclude turtles) and effectively functioned as secondary BRD's.

It is apparent that several options exist for ways of excluding bycatch from prawn trawls. In the present study we wanted to determine which of these various devices (i.e. the Nordmøre grid, blubber chute, or some type of secondary BRD) is most appropriate for use in the HR prawn-trawl fishery. Our specific goals, therefore, were 1) to assess the performance of four secondary BRD's located behind the Nordmøre grid (including designs previously tested in the Gulf of Mexico by Watson et al., 1993) in reducing smaller unwanted individuals in the HR prawn-trawl fishery; 2) to compare the two most appropriate secondary BRD's from 1) against a standard Nordmøre grid and the commercially used blubber chute; and 3) to test a standard Nordmøre grid (with no secondary BRD) against the commercially used blubber chute.

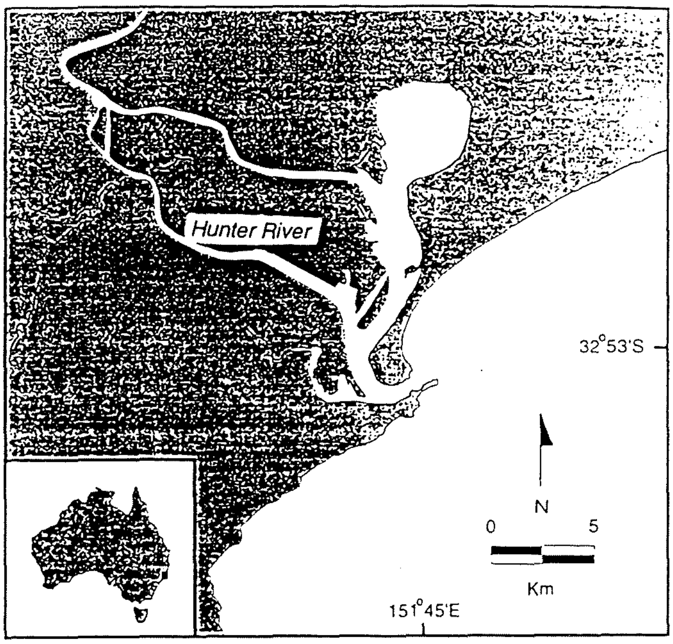

Figure 1
The location of the Hunter River in New South Wales.

Materials and methods

Two experiments were performed on commercial prawn-trawl grounds in the Hunter River (32°53'S, 151°45'E, Fig. 1), between November and December 1995 with a chartered commercial prawn-trawler (12.72 m). Three Florida flyers (mesh size=40 mm), each with a headline length of 9.14 m, were rigged in a standard triple gear configuration (see Andrew et al., 1991, for details) and towed at 2 knots across a combination of sandy and muddy bottoms in depths ranging from 2 to 8 m. Each of the identical outside nets were rigged with zippers to facilitate changing the codends (see Broadhurst et al., 1996). Because the middle net was not rigged in an identical manner to that used on the outside nets, its catch was excluded from analysis.

The codends used in the experiments measured 50 meshes long (2 m) and were constructed from 40-

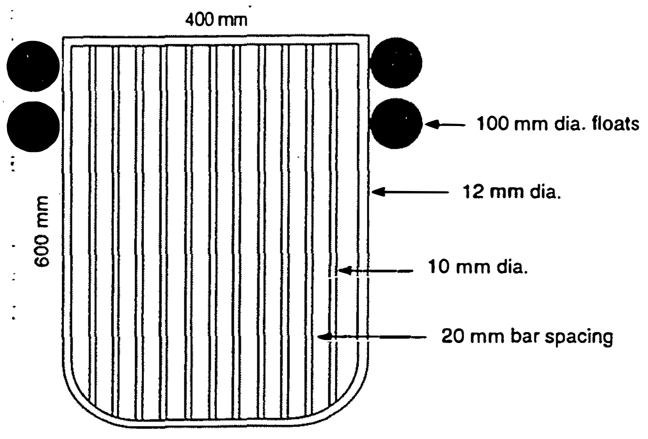

Figure 2
Diagram of the aluminum grid used in the Nordmøre grid bycatch-reducing device. dia. = diameter.

mm netting. They comprised two panels. The anterior panel was 100 meshes in circumference, 25 meshes in length, and constructed of 400/36 ply, UV-stabilized, high-density polyethylene twine. The posterior panel was 150 meshes in circumference, 25 meshes in length, and constructed of 3-mm diameter braided polyethylene twine. Two standard Nordmøre grids (each measuring 600 × 400 mm and weighing 1.9 kg, Fig. 2) were constructed and located in 2-m extension pieces (made from 400/36 ply, UV-stabilized, high-density polyethylene twine, mesh size = 40 mm) immediately anterior to each codend (Fig. 3A, see also Broadhurst and Kennelly, 1996, for details).

Experiment 1 (comparisons of secondary BRD's)

Four designs of secondary BRD's were constructed and installed into the codends described above, behind the Nordmøre grids. The first design (termed the fisheye) consisted of a stainless steel pyramid-shaped frame inserted 12 meshes to the left of the center of the top anterior section of the codend (Fig. 3B, see also Watson and Taylor[2]; Watson[3]). The second design (termed the square-mesh panel) had a panel of 50-mm knotless netting, hung on the bar and inserted into the top anterior section of the codend (Fig. 3C). The third design (termed the extended mesh funnel or EMF) comprised a guiding funnel surrounded by larger square-shaped mesh (see Watson and Taylor[2]; Watson[3]) and was located in the anterior section of the codend (Fig. 3D). The fourth design (termed the Allerio Brothers grid, Watson[4]) was constructed like the Nordmøre grid but included additional lateral fish escape windows posterior to the aluminium grid (Fig. 4).

All four designs were compared against each other, one pair of each design on the outside nets of the triple-rigged gear (i.e. 6 separate paired comparisons). The position and order of each secondary BRD was randomly determined, and during 6 days in the trawling season in the Hunter River, we completed a total of 12 replicate 30-min tows for each paired comparison. The location of each tow was randomly selected from the available prawn-trawl locations that were possible under the particular conditions. Prior to the trials, we rigged both nets with normal commercial codends to ensure that there were no differences in fishing characteristics.

Experiment 2 (comparison of two secondary BRD's, standard Nordmøre grid and blubber chute)

In this experiment, the fisheye and EMF, each attached to a Nordmøre grid, were compared against a standard Nordmøre grid (with no secondary BRD) and the commercially used blubber chute. The standard Nordmøre grid and blubber chute were also compared against each other (providing a total of five

[2] Watson, J. W., and C. W. Taylor. 1996. Technical specifications and minimum requirements for the extended funnel, expanded mesh and fisheye BRDs. Mississippi Laboratory, NMFS, NOAA, P.O. Drawer 1207, Pascagoula, MS 39567.

[3] Watson, J. W. 1996. Summay report on the status of bycatch reduction devices development. Mississippi Laboratory, NMFS, NOAA, P.O. Drawer 1207, Pascagoula, MS 39567.

[4] Watson, J. W. 1995. Mississippi Laboratory, NMFS, NOAA, P.O. Drawer, 1207, Pascagoula, MS 39567. Personal commun.

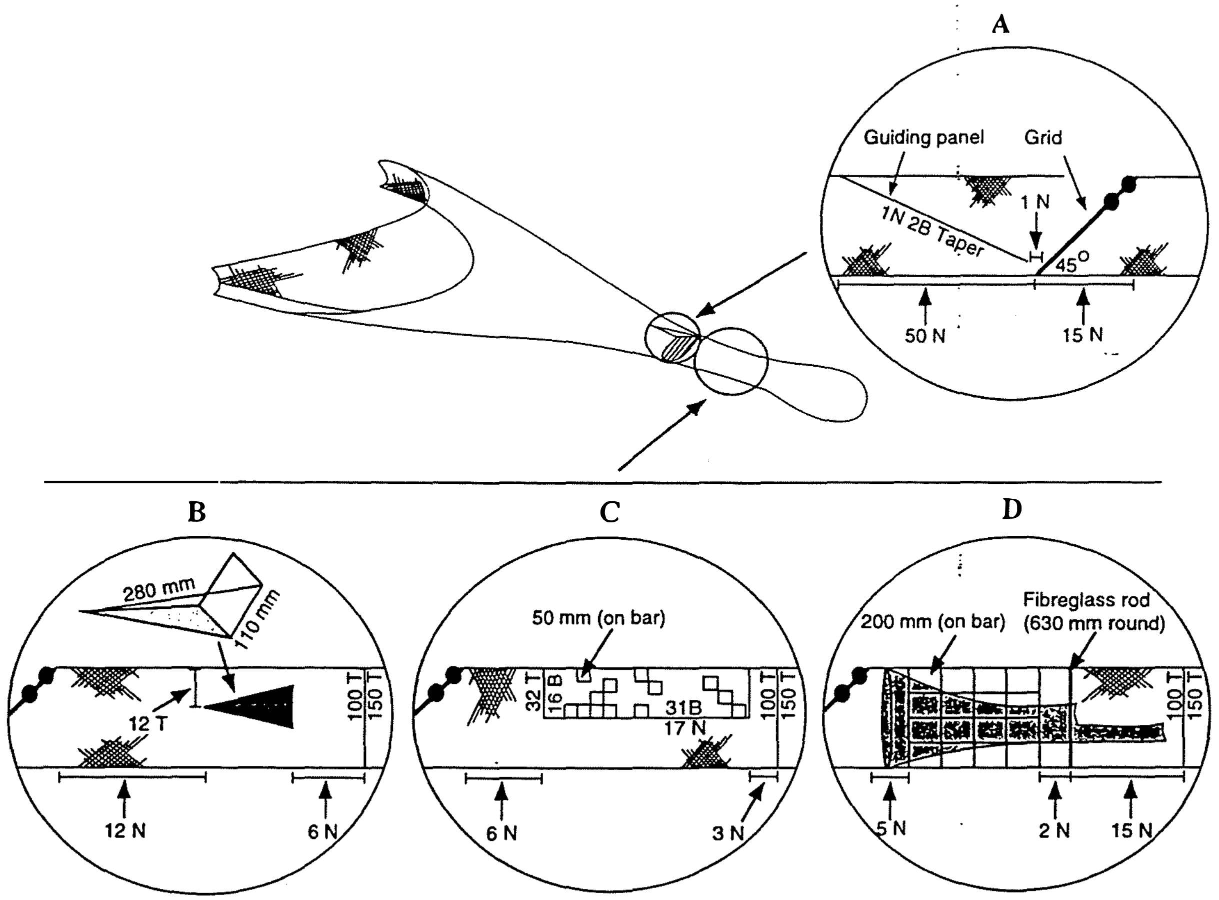

Figure 3

Diagrammatic representation of prawn-trawl and (**A**) Nordmøre grid, (**B**) fisheye, (**C**) square-mesh panel, and (**D**) extended mesh funnel (EMF) bycatch-reducing devices. T = transversals; B = bars; and N = normals.

paired comparisons). The blubber chute comprised a panel of netting (36-ply, UV-stabilized, high-density polyethylene with a mesh size of 90 mm) sewn into a funnel (with an anterior circumference of 100 meshes) located in a 2-m panel of mesh (mesh size of 40 mm) measuring 150 meshes in circumference (see Broadhurst and Kennelly, 1996, for details). The posterior point of the blubber chute was attached five meshes from the end of the 2-m panel. A 30-mesh opening (termed the escape exit) was cut immediately anterior to this point of attachment.

As was the case for experiment 1, the position and order of each design was randomly determined and used in normal commercial tows of 30-min duration. Over 8 days, we completed a total of 23 replicate tows for each of the five paired comparisons.

Data collected

After each tow in each paired experiment, the two codends were emptied onto a partitioned tray. All organisms were sorted according to species. The following data were collected from each tow: the total weight of prawns; the total weight of bycatch; the weights; numbers and sizes of commercially or recreationally (or both) important finfish (to the nearest 0.5 cm); the numbers of noncommercial or nonrecreational species; and the total numbers of noncommercial and commercial species in the assemblage. All prawns in a subsample of the total prawn catch from each tow in experiment 2 were measured in the laboratory (to the nearest 1-mm carapace length). Several species were caught in sufficient quantities to provide meaningful analyses. These were the commercially important school prawns (*Metapenaeus macleayi*) and large tooth flounder (*Pseudorhombus arsius*) and the commercially unimportant fortesque (*Centropogon australis*), narrow banded sole (*Synclidopus macleayanus*), bridle goby (*Arenigobius bifrenatus*), and catfish (*Euristhmus lepturus*).

Data from all replicates that had sufficient numbers of each variable (defined as >2 fish in at least 8

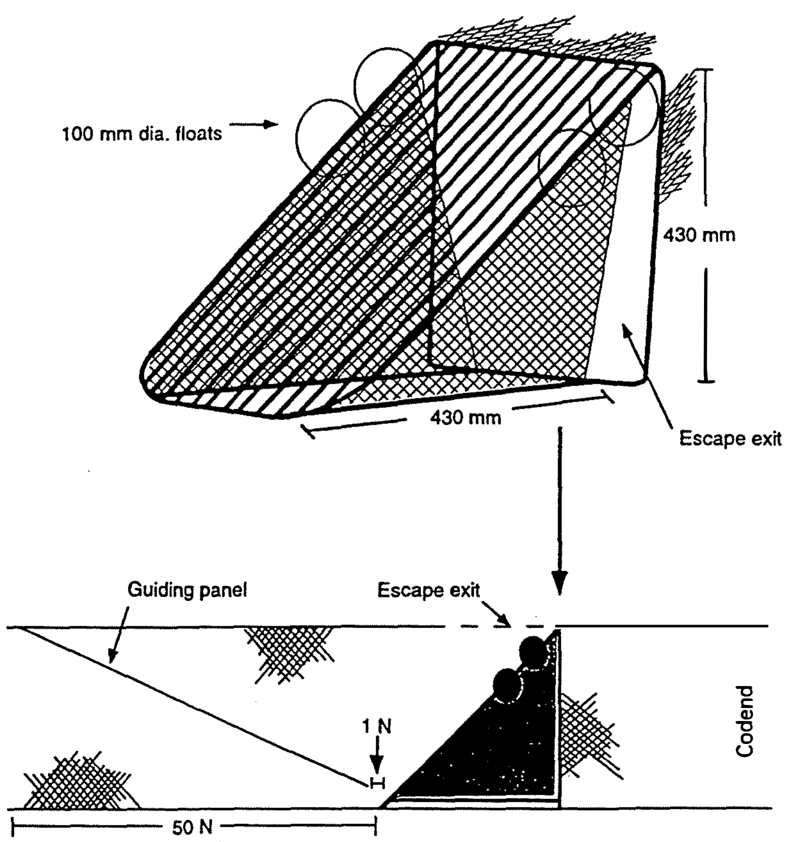

Figure 4
Diagrammatic representation of the Allerio Brothers grid. dia = diameter.

replicates) in experiment 1 were analyzed by using two-tailed, paired t-tests. Because a previous experiment in the Clarence River prawn-trawl fishery showed that the Nordmøre grid caught more prawns than the blubber chute (Broadhurst and Kennelly, 1996), in experiment 2 we tested the hypothesis that each of the three designs incorporating a Nordmøre grid caught more prawns but less bycatch than the commercially used blubber chute. These data were analyzed by using one-tailed paired t-tests. Size frequencies of prawns from experiment 2 were graphed and compared by using two-sample Kolmogorov-Smirnov tests (P=0.05).

Results

Experiment 1 (comparisons of secondary BRD's)

Apart from a significant reduction in the number of noncommercial species caught as bycatch by the Allerio Brothers grid, compared with the number caught with the square-mesh panel, there were no other detectable differences between any of the secondary BRD's tested (Table 1). However, because previous studies in the Gulf of Mexico showed that the EMF and fisheye were most effective in excluding small fish from the codend (Watson and Taylor[2]; Watson[3]), these two designs were tested further in experiment 2.

Experiment 2 (comparison of two secondary BRD's, standard Nordmøre grid and blubber chute)

Compared with the commercially used blubber chute, the standard Nordmøre grid, EMF, and fisheye all significantly increased the weight of prawns caught (means increased by 24%, 41%, and 23%, respectively) and decreased the weight of total bycatch (means reduced by 58%, 45%, and 55%, respectively) and number of noncommercial species in bycatch (Fig. 5, A, B, and H; Table 2). The fisheye also significantly reduced the mean number of catfish caught by 79.5% (there were insufficient catfish from the

Table 1

Summaries of two–tailed paired *t*–tests in a series of comparisons of various secondary BRD's in experiment 1. ** = significant ($P<0.01$); * = significant ($P<0.05$); *n* = the number of replicates that had sufficient data available for analysis (i.e. >2 fish in 8 replicates).

	Allerio Bros. vs. EMF			Allerio Bros. vs. square–mesh			Allerio Bros. vs. fisheye		
	Paired *t*–value	*P*	*n*	Paired *t*–value	*P*	*n*	Paired *t*–value	*P*	*n*
Wt. of prawns	–0.602	0.559	12	0.193	0.850	12	0.689	0.505	12
Wt. of total bycatch	–0.967	0.354	12	–1.827	0.095	12	0.958	0.358	12
No. of fortesque	0.000	0.999	9	0.886	0.398	10	2.200	0.052	11
No. of noncommercial sp.	–0.860	0.407	12	–2.46	0.031*	12	–1.146	0.276	12
No. of commercial sp.	–0.232	0.821	12	1.517	0.157	12	–1.698	0.120	12

	Square–mesh vs. EMF			Fisheye vs. square–mesh			Fisheye vs. EMF		
	Paired *t*–value	*P*	*n*	Paired *t*–value	*P*	*n*	Paired *t*–value	*P*	*n*
Wt. of prawns	–0.225	0.826	12	–1.36	0.200	12	–1.795	0.100	12
Wt. of total bycatch	–0.318	0.756	12	–1.821	0.095	12	–0.513	0.618	12
No. of fortesque	0.808	0.440	10	–0.683	0.544	8	–0.455	0.659	10
No. of noncommercial sp.	1.216	0.249	12	–1.431	0.180	12	–1.383	0.194	12
No. of commercial sp.	–0.890	0.392	12	–0.364	0.722	12	–1.190	0.256	12

Table 2

Summaries of one-tailed paired *t*–tests in a series of comparisons of various BRD's in experiment 2. Ng = Nordmøre grid. ** = significant ($P<0.01$); * = significant ($P<0.05$); *n* = the number of replicates that had sufficient data available for analysis (i.e. >2 fish in 8 replicates).

	Standard Ng vs. blubber chute			EMF vs. blubber chute			Fisheye vs. blubber chute		
	Paired *t*–value	*P*	*n*	Paired *t*–value	*P*	*n*	Paired *t*–value	*P*	*n*
Wt. of prawns	2.864	0.004**	23	3.764	0.0005**	23	2.020	0.027*	23
Wt. of total bycatch	3.515	0.001**	23	2.930	0.003**	23	3.306	0.002**	23
Wt. of large tooth flounder	0.979	0.173	14	0.729	0.239	14	1.394	0.103	8
No. of large tooth flounder	0.061	0.476	14	–0.879	0.802	14	0.747	0.239	8
No. of fortesque	0.286	0.389	19	–0.261	0.601	20	0.761	0.228	18
No. of narrow banded sole	1.064	0.164	8	—	—	—	1.440	0.090	10
No. of bridled goby	–0.414	0.654	8	—	—	—	–0.078	0.531	11
No. of catfish	—	—	—	—	—	—	3.490	0.003**	10
No. of noncommercial sp.	2.626	0.007**	23	2.040	0.026*	23	1.931	0.033*	22
No. of commercial sp.	–1.190	0.876	23	0.000	0.500	23	0.282	0.390	23

	Standard Ng vs. fisheye			Standard Ng vs. EMF		
	Paired *t*–value	*P*	*n*	Paired *t*–value	*P*	*n*
Wt. of prawns	0.618	0.271	23	–1.418	0.914	23
Wt. of total bycatch	0.721	0.239	23	0.512	0.307	23
Wt. of large tooth flounder	0.410	0.346	9	–0.507	0.689	13
No. of large tooth flounder	1.835	0.052	9	–0.456	0.672	13
No. of fortesque	–0.647	0.736	16	–0.128	0.449	19
No. of narrow banded sole	–0.147	0.556	9	0.741	0.241	8
No. of bridled goby	—	—	—	3.468	0.004**	8
No. of catfish	—	—	—	—	—	—
No. of noncommercial sp.	0.530	0.300	23	2.688	0.007*	23
No. of commercial sp.	1.156	0.130	23	0.755	0.229	23

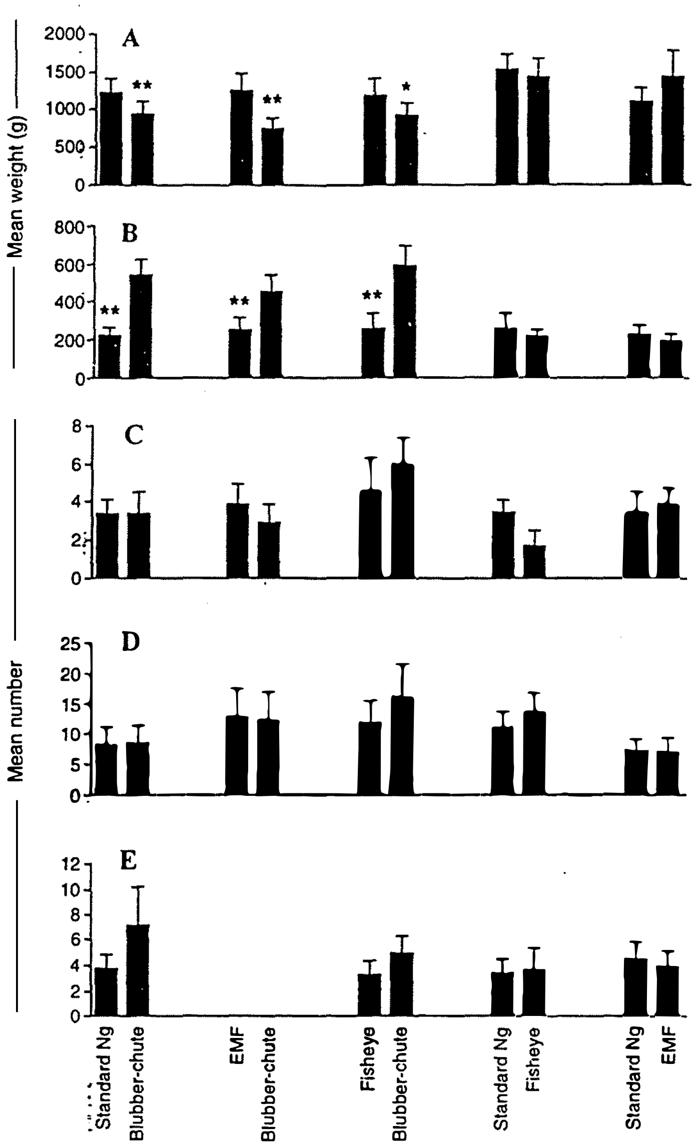

Figure 5

Differences in mean catch (± SE) between the various designs of (A) the weight of prawns (*Metapenaeus macleayi*), (B) the weight of total bycatch, (C) the number of large tooth flounder (*Pseudorhombus arsius*), (D) the number of fortesque (*Centropogon australis*), (E) the number of narrow banded sole (*Synclidopus macleayanus*), (F) the number of bridle goby (*Arenigobius bifrenatus*), (G) the number of catfish (*Euristhmus lepturus*), (H) the number of noncommercial species, and (I) the number of commercial species. * = $P<0.05$; ** = $P<0.01$. Ng = Nordmøre grid; EMF = extended mesh funnel.

standard Nordmøre grid and EMF for meaningful analyses) (Fig. 5G; Table 2). There were no significant differences detected between the standard Nordmøre grid and fisheye, whereas the EMF caught significantly fewer bridled gobies and noncommercial species than did the standard Nordmøre grid (Fig. 5, F and H; Table 2).

Two sample Kolmogorov-Smirnov tests comparing the size-frequency distributions for school prawns showed that, apart from a significant difference between the standard Nordmøre grid and the EMF (Fig. 6E), there were no other differences in the relative size-compositions between any of the codends tested in experiment 2.

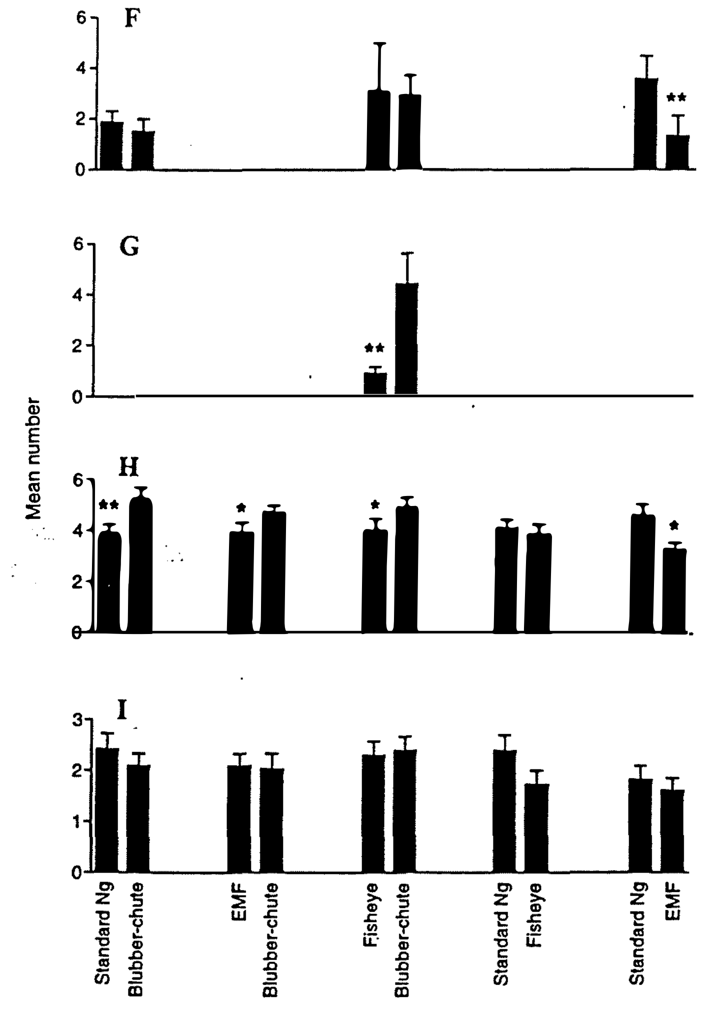

Figure 5 (continued)

Discussion

This study has confirmed the effectiveness of the Nordmøre grid in reducing bycatch while maximizing catches of prawns in NSW estuarine prawn-trawl fisheries (see also Broadhurst and Kennelly, 1996; Broadhurst et al., 1996). By comparing several secondary BRD's attached to a Nordmøre grid, we have also provided information on the relative effectiveness of these designs and their suitability in the HR prawn-trawl fishery.

The results from experiment 1 showed that apart from a significant reduction in the number of noncommercial species with the Allerio Brothers grid, compared with the square-mesh panel, there were no detectable differences in the relative performance of any of the secondary BRD's tested (Table 1).

Compared with the commercially used blubber chute, all three designs incorporating Nordmøre grids in experiment 2 (the standard Nordmøre grid and the Nordmøre grid incorporating the EMF and fisheye) significantly increased the catches of prawns (by 24%, 41%, and 23%, respectively) while significantly reducing the total bycatch (by 58%, 45%, and 55%, respectively) (Fig. 5; Table 2). In earlier papers (Broadhurst and Kennelly, 1996; Broadhurst et al., 1996), we concluded that the prawn-retention characteristics of the Nordmøre grid were attributed to its ability to remove seaweed and debris more effectively. In the present study we observed that, at the end of each tow, those designs incorporating the Nordmøre grid were observed to be relatively free of seaweed and debris, whereas the blubber chute often had large quantities entangled between the meshes, which may have decreased the lateral openings between the meshes in the blubber chute and contributed towards the escape of prawns with this design. Further, because Kolmogorov-Smirnov tests

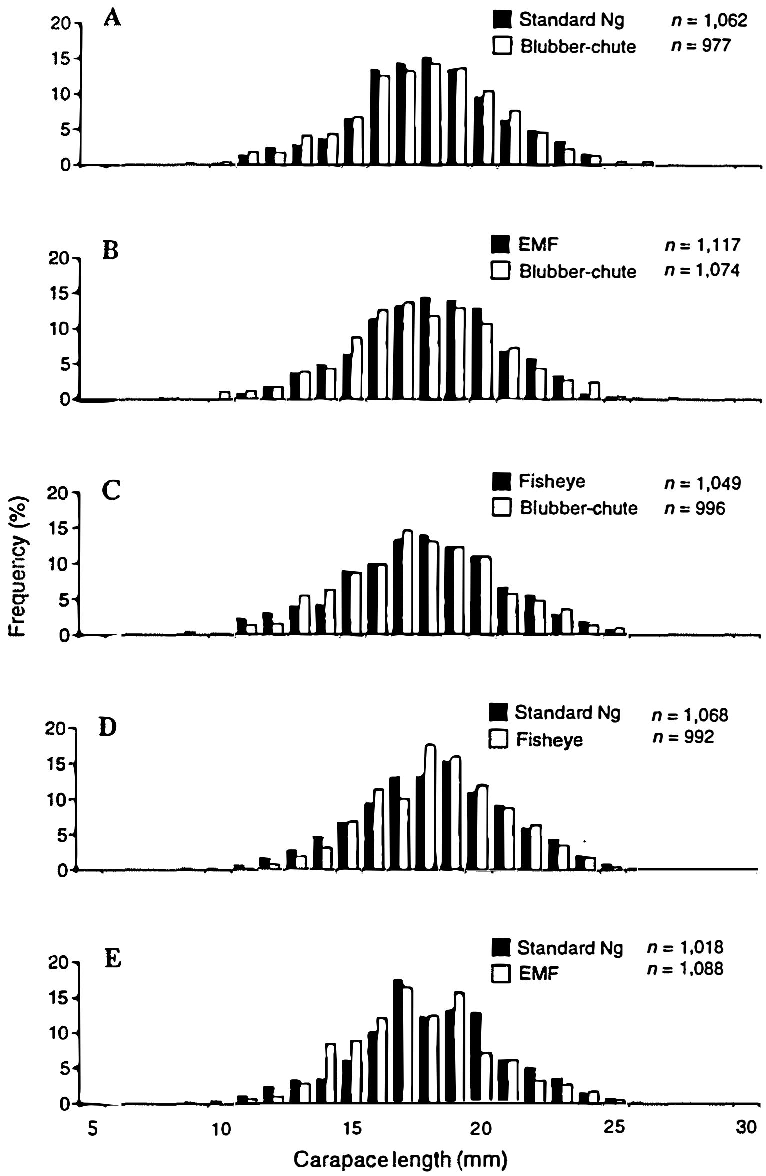

Figure 6

Size-frequency distributions of school prawns (*Metapenaeus macleayi*) caught with (**A**) the standard Nordmøre grid and blubber chute, (**B**) the extended mesh funnel and blubber chute, (**C**) the fisheye and blubber chute, (**D**) the standard Nordmøre grid and fisheye, and (**E**) the standard Nordmøre grid and extended mesh funnel.

on the size-frequency compositions of school prawns failed to detect any difference between the standard Nordmøre grid and the blubber chute (Fig. 6A), such escapees were probably of all sizes. Another hypothesis to explain the loss of prawns from the blubber chute is that some prawns became entangled within the tentacles and large subumbrella of captured jelly fish and were directed, along with the jellyfish, out through the escape exit. In contrast, the long guiding panel and smooth contours of the Nordmøre grid may have allowed the prawns to detach from the jellyfish and thus enabled them to pass into the codend.

Apart from a significant reduction in the numbers of bridle goby and noncommercial species caught by the EMF compared with the number caught by the standard Nordmøre grid in experiment 2, there were no other significant differences between the relative performance of the secondary BRD's and the standard Nordmøre grid (Fig. 5; Table 2). Given these results, therefore, it is likely that most of the fish escaped at the standard Nordmøre grid. While the relatively small bar spacings (20 mm) may have been sufficient to exclude a large number of individuals simply because of their size, it is also possible that smaller fish were able to escape passively. For example, in a previous paper (Broadhurst et al., 1996) we provided evidence that some small bream (*Acanthopagrus australis*) detected the grid in advance (either visually or by means of their lateral lines). These fish may have then orientated away from the grid into an area of reduced water flow behind the guiding panel. The geometric attitude of the grid possibly directed some of these fish out of the codend without mechanical separation through the bars.

Whatever the mechanism of escape, we conclude that, given the effectiveness of the Nordmøre grid in excluding large quantities of bycatch, there appears to be little advantage in attaching secondary BRD's behind grids in the HR prawn-trawl fishery. Because of this, the additional labor and time involved in the manufacture, maintenance, and deployment of these secondary BRDs is clearly unwarranted.

Like several recent studies, this study has shown that there is great utility for the Nordmøre grid in many of NSW estuarine prawn-trawl fisheries. The increases in prawn catches and reductions in bycatch shown in our work in these fisheries have already led many commercial fishermen to use the standard Nordmøre grid in preference to the traditional blubber chute. Such independent and voluntary adoption of the Nordmøre grid by industry may eventually lead to further refinements in design and should facilitate widespread acceptance of this bycatch-reduction gear throughout most of NSW's estuarine prawn-trawl fisheries.

Acknowledgments

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The composite square-mesh panel: a modification to codends for reducing unwanted by-catch and increasing catches of prawns throughout the New South Wales oceanic prawn-trawl fishery.

Broadhurst, M.K., and S.J. Kennelly, 1997.

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The composite square-mesh panel: a modification to codends for reducing unwanted bycatch and increasing catches of prawns throughout the New South Wales oceanic prawn-trawl fishery

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Abstract.–The effectiveness of a new bycatch reduction device (BRD) was tested across a wide geographical range to determine its use in the NSW oceanic prawn-trawl fishery. Using four commercial trawlers, each from a different port located in the fishery, we compared the catches and bycatches from conventional trawls with those from trawls containing composite panels of netting (60 mm and 40 mm) hung on the bar and inserted into the top anterior section of the codend (termed the composite-panel codend). This panel was designed so that the 40-mm mesh 1) would allow some small fish to escape and 2) would distribute the load anterior and lateral to the 60-mm mesh (which was located in an area where waterflow was thought to be greatest), allowing the 60-mm mesh to remain open and thus facilitate the removal of larger fish. Simultaneous comparisons against a control codend showed that the composite-panel codend significantly reduced the weights of discarded bycatch at all four locations (means reduced by 23.5% to 41%) and the numbers of juveniles of commercially important species, such as whiting, *Sillago* sp. (by up to 70%). At three of the locations the composite-panel significantly increased the catches of the prawn *Penaeus plebejus* (5.5% to 14%) and, although not statistically significant, showed a similar trend at the fourth location (mean increase of 4%). As a result of this study, the composite-panel codend has been adopted and voluntarily used by fishermen throughout the New South Wales oceanic prawn-trawl fishery.

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In New South Wales (NSW), Australia, oceanic prawn-trawling involves over 300 vessels operating from 11 major ports along 1,000 km of coastline and is valued at approximately A$17 million per annum. Vessels operating in this fishery primarily target the eastern king prawn, *Penaeus plebejus*, although a significant portion of the total value in the fishery is derived from the sale of legally retained bycatch (termed "by-product")—comprising several species of fish, crustaceans, and cephalopods. As in the majority of the world's prawn-trawl fisheries, however, significant numbers of nontarget organisms are also captured and discarded in this fishery (for reviews see Saila, 1983; Andrew and Pepperell, 1992; Alverson et al., 1994; Kennelly, 1995). In NSW, this discarded bycatch includes individuals of byproduct species that are smaller than the minimum commercial size and a large assemblage of noncommercial species (see Kennelly, 1995).

Unwanted bycatch has been reduced in several of the world's prawn-trawl fisheries by means of modifications to codends that contain bycatch reduction devices (BRD's) (e.g. Watson et al., 1986; Matsuoka and Kan, 1991; Isaksen et al., 1992; Rulifson et al., 1992; Renaud et al., 1993; Christian and Harrington[1]). In general, these modifications have involved either 1) some form of rigid structure that functions by mechanically separating larger unwanted individuals or 2) a strategically placed escape "window" made of netting that works by exploiting behavioral differences between prawns and smaller finfish. Although many of these modifications have proven effective in reducing bycatch from prawn trawls, sometimes they have not been favored by commercial fishermen (see Kendall, 1990; Renaud et al., 1993) because of their size (in relation to the codend), their often complex design (e.g. Mounsey et al., 1995), and, in some cases, their failure to maintain prawn catches at the same levels as conventional trawls (e.g. Rulifson et al., 1992; Robins-Troeger et al., 1995; Christian and Harrington[1]).

One modification that has been successfully tested and adopted in

[1] Christian, P., and D. Harrington. 1987. Loggerhead turtle, finfish and shrimp retention studies on four excluder devices (TEDs). *In* Proceedings of the nongame and endangered wildlife symposium; 8–10 September 1987, Georgia, p. 114–127. Dep. Nat. Resources, Social Circle, GA.

several trawl fisheries in the North Atlantic involves inserting large panels of square-mesh in codends (Robertson and Stewart, 1988; Carr, 1989; Briggs, 1992; Isaksen and Valdermarsen[2]; Suuronen[3]). These studies have shown that square-mesh panels often reduce the bycatch of juvenile roundfish while retaining a large proportion of the targeted catch. In previous experiments (Broadhurst and Kennelly, 1994, 1995, 1996; Broadhurst et al., 1996), we have shown that relatively small panels of square-mesh, inserted into the top anterior sections of penaeid prawn-trawl codends, allowed large numbers of small fish to escape without any losses of prawns. In these experiments, the majority of fish were thought to have been herded together in the narrow anterior section of the codend, immediately in front of the catch (see also Wardle, 1983). This concentration of fish was thought to upset the balance of the school and to initiate a response in the fish to escape by swimming towards the sides and top of the net and out through the open square-meshes. In addition, we showed that codend circumference and differences in hydrodynamic pressure had significant effects on the rates of movement of these fish through the square-mesh panel. The reaction of prawns to these stimuli was considered to be fairly limited, given their inability to maintain an escape response to trawls (see Lochhead, 1961; Main and Sangster, 1985).

In a recent experiment (Broadhurst and Kennelly, 1996) in one location in NSW, we tested a new design of codend, comprising composite panels of square-shaped mesh (referred to as the composite-panel codend), designed for and located in the codend, to take advantage of the theory discussed above. The results showed that this design was effective in reducing up to 40% of the total unwanted bycatch and up to 70% of the numbers of juveniles of commercially important species with no significant reduction in the catches of prawns and other commercially important species. Although not validated statistically, there was also some evidence to suggest that the trawls with the composite square-mesh panel retained, on average, slightly more prawns than a conventional trawl (means increased by up to 3%). This latter result, in particular, led numerous local fishermen to install the composite-panel voluntarily in their trawls and use it as part of normal commercial operations.

To assess the performance of this design throughout the full geographic range of this fishery (encompassing the range of fishing conditions and catches) and to promote its voluntary acceptance, our specific goals in the present study were to investigate the effectiveness of the composite-panel under normal commercial operations at four major ports along the NSW coast in 1) reducing unwanted bycatch, 2) maintaining catches of commercially important byproduct, and 3) increasing catches of prawns.

Materials and methods

This study was performed between December 1995 and February 1996 with four commercial vessels (see Table 1 for details) on prawn-trawl grounds offshore from four ports (Port Stephens, Southwest Rocks, Yamba, and Ballina) in New South Wales, Australia (Fig. 1). Each vessel was rigged with three Florida flyers (mesh size=42 mm) in a standard triple gear configuration (see Kennelly et al., 1993 for details), towed at 2.5 knots. Each of the identical outside nets on each vessel were rigged with zippers (no. 10 nylon open-ended auto-lock plastic slides) to facilitate removal and attachment of the codends. Because each of the middle nets were not rigged in exactly the same way as the outside nets, their catches were excluded from any analysis.

The codends used in the study measured 58 meshes long (2.3 m) and were constructed from 40-mm mesh

[2] Isaksen, B., and J. W. Valdemarsen. 1986. Selectivity experiments with square mesh codends in bottom trawl. Int. Coun. Explor. Sea council meeting 1986/B: 28, 18 p.

[3] Suuronen, P. 1990. Preliminary trials with a square mesh codend in herring trawls. Int. Coun. Explor. Sea, council meeting 1990/B: 28, 14 p.

Table 1

Summary of vessels, trawl headline lengths, and depths trawled for each of the four ports.

Port	Vessel and (length in m)		Trawl headline length for each net (m)	Depth trawled (m)
Port Stephens	*Fairwind*	(16)	16.45	75–88
Southwest Rocks	*Shelley-Anne*	(13.7)	10.97	47–53
Yamba	*L-Margo*	(15.93)	12.8	20–49
Ballina	*New Avalon*	(18.5)	14.63	29–55

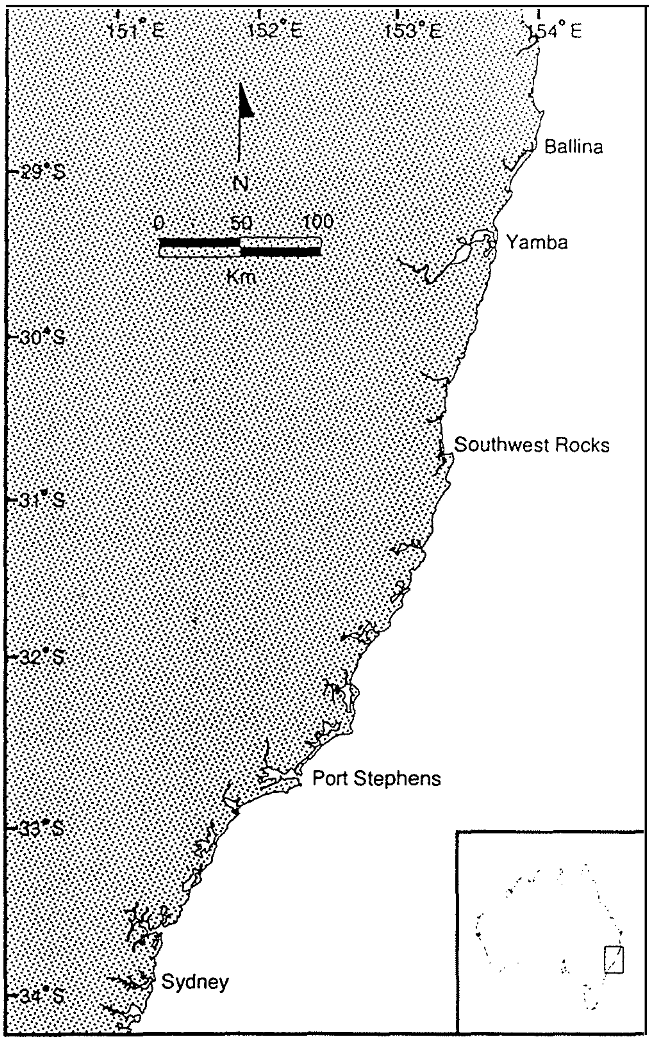

Figure 1

Map of New South Wales showing locations of the four ports that were sampled (Ballina, Yamba, Southwest Rocks, and Port Stephens).

netting and 48-ply twine (Fig. 2). They comprised two sections: the anterior section was 100 meshes in circumference, 33 meshes in length, and attached to a zipper; the posterior section was 150 meshes in circumference and 25 meshes in length. Two designs of codend were compared. The control codend was made entirely of diamond-shaped meshes (Fig. 2A). The second codend (termed the composite-panel codend) was similar to the control but had composite panels made of 60-mm and 40-mm netting cut on the bar and inserted into the top of the anterior section (Fig. 2B—see also Broadhurst and Kennelly, 1996). The composite-panel codend was designed so that the load was distributed anteriorly and laterally to the panel of 60-mm square-mesh, allowing this 60-mm panel to remain open. We predicted that 1) large numbers of fish would escape through this panel, located at the point where waterflow was thought to be greatest and that 2) in addition to reducing load on the 60-mm panel, the 40-mm square-mesh would also facilitate the escape of smaller fish.

The two codends were compared with each other in independent, paired trials, with the two outside nets of each vessel at each location. The codends were used in normal commercial tows of 90-min duration and alternated after each shot (to eliminate biases between different trawls and sides of the vessels). Because some significant effects of a delay in haulback (the period between slowing the vessel and engaging the winch to haul the trawl) were detected in a previous experiment (Broadhurst et al., 1996), all tows were performed with no delay in haulback. The location of each tow was randomly selected from the available prawn-trawl locations that were possible under the fishing conditions. During a period of four nights at locations offshore from each of the four ports, we completed a total of 16 replicate tows (i.e. four separate paired comparisons of 16 replicate tows each throughout the fishery).

After each tow, the two codends were emptied onto a partitioned tray. Prawns and all commercially important species larger than the minimum legal size (retained commercials) were separated. The remaining bycatch (termed "discarded by-catch") was then sorted. This included individuals of commercially important species that were smaller than the minimum legal size ("discarded commercials"). Data collected from each tow were as follows: the total weight of king prawns and a subsample (50 prawns from each codend) of their sizes (to the nearest 1-mm carapace length); the weight of the discarded bycatch; the weights, numbers, and sizes (to the nearest 0.5 cm) of retained and discarded commercial species; the weights and the numbers of the most commonly occurring noncommercial species; and the total numbers of discarded commercial species. Several species (commercial and noncommercial) were caught in sufficient numbers to enable meaningful comparisons (see Table 2).

Data at each port for all replicates that had sufficient numbers of each variable (defined as >2 individuals in at least 8 replicates) were analyzed with one-tailed, paired t-tests (i.e. four separate analyses). Because a previous experiment had shown that trawls with the composite-panel have the potential to retain more prawns than conventional trawls (Broadhurst and Kennelly, 1996), we tested the hypothesis that the composite-panel codend caught more prawns but less total bycatch than the control codend. Where analyses provided similar results for weights and numbers of taxa, only data about numbers were included in the figures to conserve space. Size frequencies of prawns, as well as discarded stout

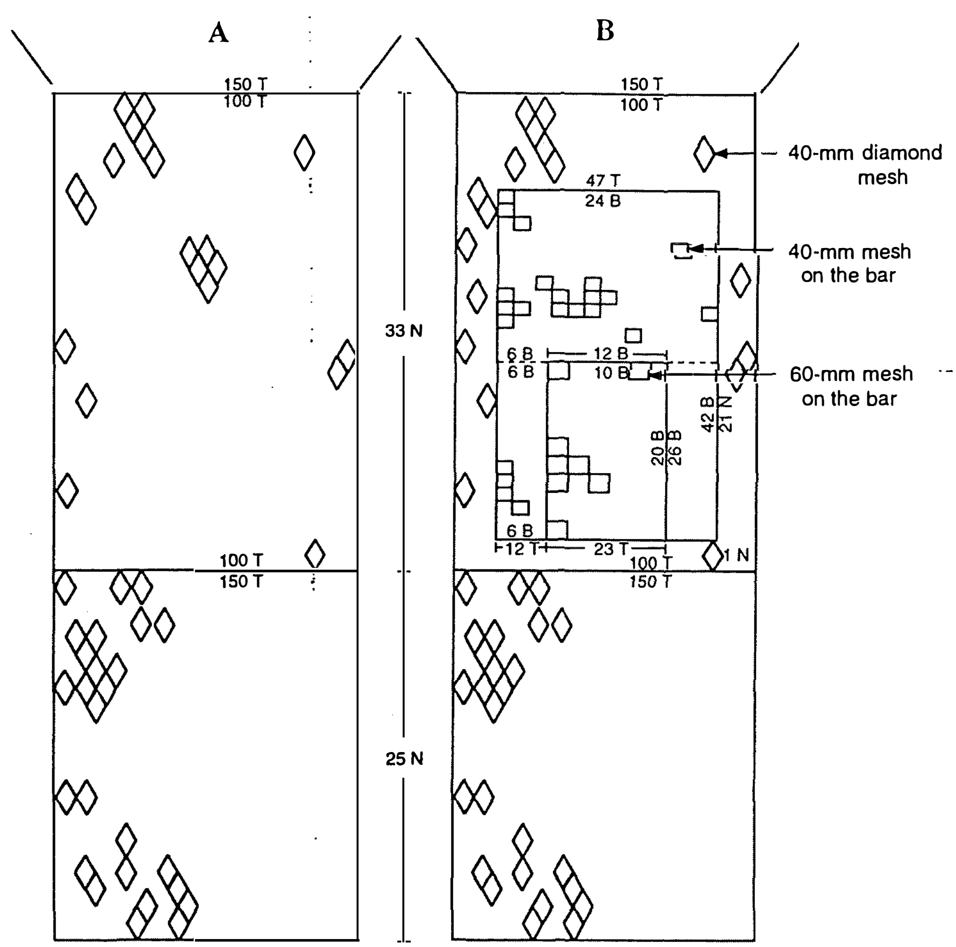

Figure 2

Diagrammatic representation of (**A**) the control codend and (**B**) the composite-panel codend. T = transversals; B = bars; and N = normals.

whiting, red spot whiting, and retained red mullet (where there were sufficient numbers) were plotted for each port and compared with two-sample Kolmogorov-Smirnov tests (P=0.05).

Results

Compared with the control codend, the composite-panel codend significantly reduced the weights of discarded bycatch (means reduced from 23.5% to 41%) at all four ports and significantly increased the catches of prawns at Port Stephens, Yamba, and Ballina (means increased by 14%, 5.5%, and 6%, respectively) (Fig. 3, A and B; Table 3). Although not to a significant degree (4%), the composite-panel codend used at Southwest Rocks also retained, on average, more prawns than the control codend (Fig. 3A). There were no significant reductions detected in the numbers and weights of commercial species retained by the composite-panel codend at any of the four ports (Fig. 3; Table 3).

The mean numbers and weights of discarded red spot whiting and stout whiting were reduced by the composite-panel codend at all locations where there were sufficient numbers to enable meaningful analysis (means reduced by up to 73%) (Fig. 3, F–G; Table 3). At Port Stephens, the composite-panel codend significantly reduced the numbers and weights of discarded john dory (by 50% and 57%, respectively) and blackeyes (by 45%) (Fig. 3, H and M; Table 3). There was a significant reduction in the numbers and weights of flutefish at Southwest Rocks (by 37% and 34%, respectively) and in the numbers and weights of red bigeye at Yamba (by 38.5% and 44%, respectively) and Ballina (by 35%) (Fig. 3, L and K; Table 3). There was also a significant reduction in the numbers and weights of leatherjacket (by 17% and 31%, respectively) and gurnard (by 41.5%) with the composite-panel codend at Ballina (Fig. 3, J and N; Table 3).

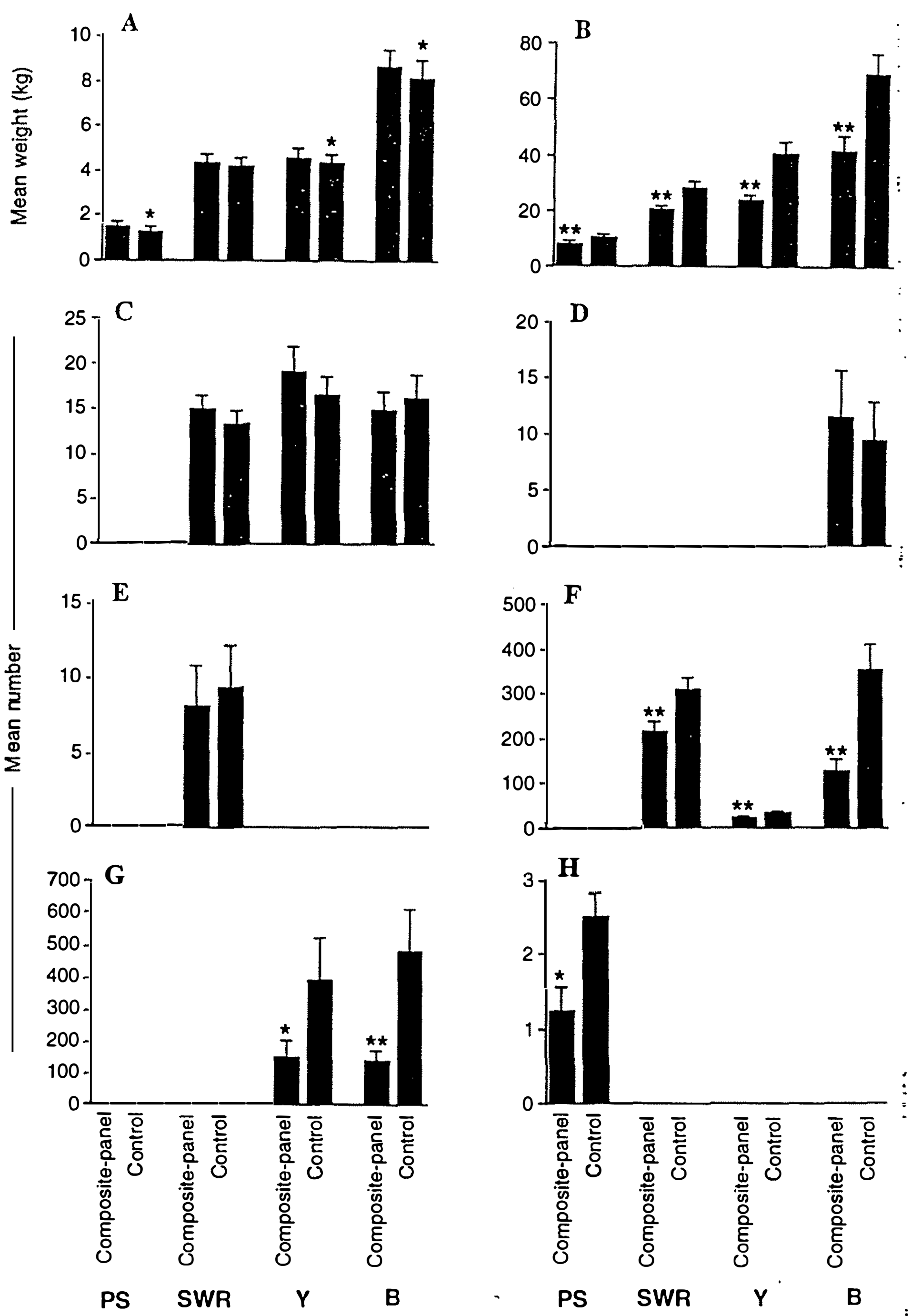

Figure 3

Differences in mean catches (± SE) between the control and composite-panel codends at each of the four ports: the weights of (**A**) prawns and (**B**) discarded bycatch; and the numbers of (**C**) retained octopus, (**D**) retained red mullet, (**E**) retained red spot whiting, (**F**) discarded red spot whiting, (**G**) discarded stout whiting, (**H**) discarded john dory, (**I**) discarded eastern blue spot flathead, (**J**) discarded leather jacket, (**K**) discarded red bigeye, (**L**) discarded flute fish, (**M**) discarded blackeyes, and (**N**) discarded gurnard. ** = significant ($P<0.01$); * = significant ($P<0.05$); PS = Port Stephens ; SWR = Southwest Rocks; Y = Yamba; and B = Ballina.

Two-sample Kolmogorov-Smirnov tests, comparing the size-frequency distributions for prawns, discarded red spot whiting, and retained red mullet measured from each sample at each site showed no differences in the relative size compositions of fish retained by the two codends (Figs. 4, 5, and 6C). There were no signifi-

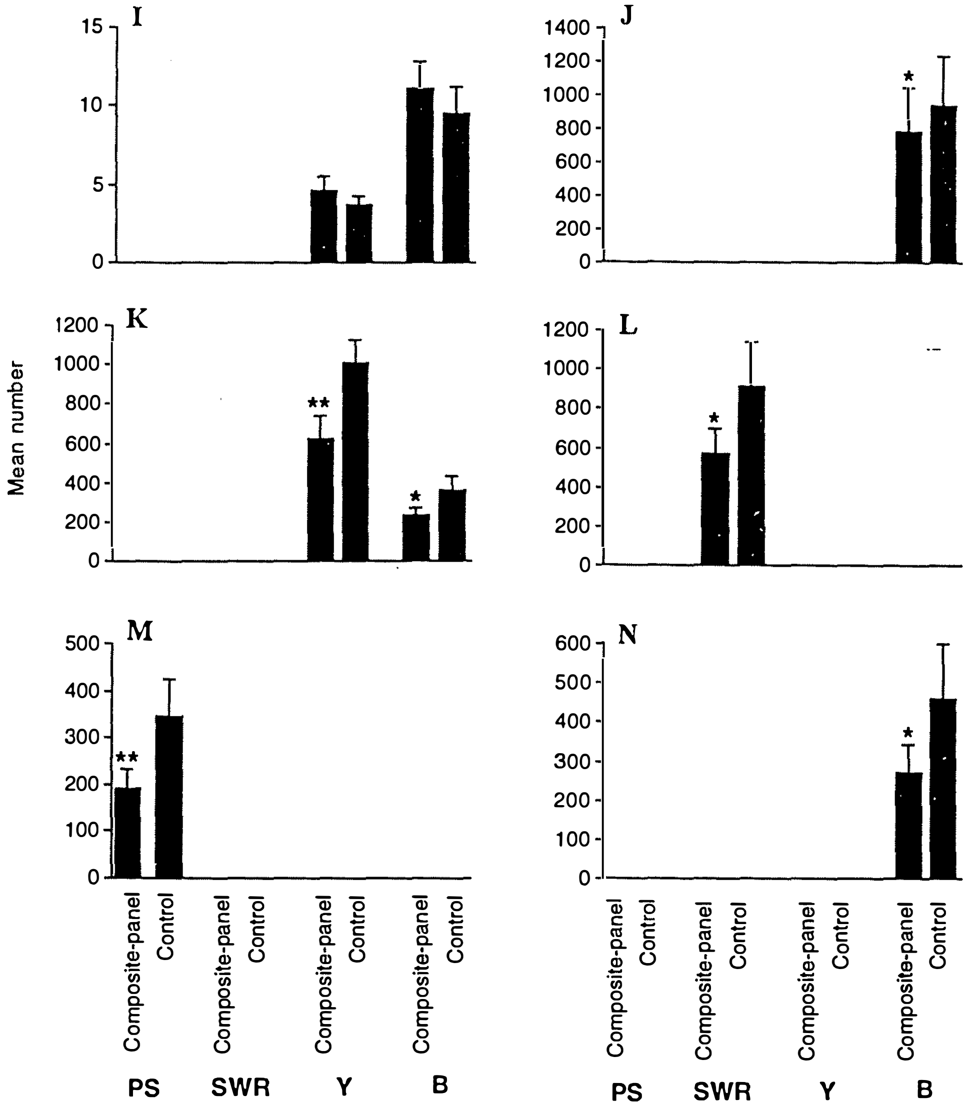

Figure 3 (continued)

Table 2

List of species caught in sufficient quantities to permit analyses.

Scientific name	Common name	Scientific name	Common name
Penaeus plebejus	eastern king prawn	*Platycephalus caeruleopunctatus*	eastern blue spot flathead
Octopus spp.	octopus	*Platycephalus richardsoni*	tiger flathead
Sepia spp.	cuttlefish	*Centroberyx affinis*	redfish
Sepioteuthis australia	southern calamary	*Paramonacantus filicauda*	threadfin leatherjacket[1]
Ibacus sp.	smooth bug	*Priacanthus macracanthus*	big redeye[1]
Pecten fumatus	scallop	*Macrorhamphosus scolopax*	flute fish[1]
Upeneichthys lineates	red mullet	*Apogonops anomalus*	blackeye[1]
Sillago flindersi	red spot whiting	*Lepidotrigla argus*	gurnard[1]
Sillago robusta	stout whiting		
Zeus faber	john dory		

[1] Denotes noncommercial species

Table 3

Summaries of one-tailed paired t-tests comparing the composite-panel and control codends. pt-v = paired t-value; n = number of replicates; all weights are in kilograms. disc = discarded; ret = retained; s. calamari = southern calamari; s. bug = smooth bug; rsw = red spot whiting ; sw = stout whiting; ebs = eastern bluespot flathead; and comm. sp. = commercial species. Significant P-values are in bold; insufficient data are marked by a dash.

	Port Stephens			Southwest Rocks			Yamba			Ballina		
	pt-v	P	n	pt-v	P	n	pt-v	P	n	pt-v	P	n
Wt of prawns	2.139	**0.024**	16	1.366	0.090	16	2.104	**0.026**	16	1.963	**0.034**	16
Wt of disc bycatch	4.467	**0.0002**	16	2.930	**0.0001**	16	5.518	0.0001	16	8.254	**0.0001**	16
No. of ret octopus	—	—	—	−0.913	0.812	16	−1.959	0.964	15	0.904	0.190	16
Wt of ret octopus	—	—	—	−0.868	0.800	16	−0.298	0.615	15	−0.341	0.631	16
No. of disc octopus	—	—	—	0.000	•	10	—	—	—	—	—	—
Wt of disc octopus	—	—	—	−0.171	0.566	10	—	—	—	—	—	—
No. of ret cuttlefish	—	—	—	−0.324	0.624	13	—	—	—	—	—	—
Wt of ret cuttlefish	—	—	—	−0.434	0.664	13	—	—	—	—	—	—
No. of disc cuttlefish	0.631	0.272	10	0.500	0.312	16	—	—	—	—	—	—
Wt of disc cuttlefish	0.165	0.436	10	0.995	0.167	16	—	—	—	—	—	—
No. of ret s. calamari	—	—	—	1.011	0.166	13	—	—	—	—	—	—
Wt of ret s. calamari	—	—	—	1.532	0.075	13	—	—	—	—	—	—
No. of disc s. calamari	—	—	—	0.703	0.248	12	—	—	—	—	—	—
Wt of disc s. calamari	—	—	—	0.887	0.197	12	—	—	—	—	—	—
No. of ret s. bug	0.452	0.329	13	—	—	—	—	—	—	—	—	—
Wt of ret s. bug	1.214	0.124	13	—	—	—	—	—	—	—	—	—
No. of disc s. bug	—	—	—	−0.254	0.597	8	−0.541	0.701	15	—	—	—
Wt of disc s. bug	—	—	—	0.344	0.371	8	−0.593	0.718	15	—	—	—
No. of disc scollop	—	—	—	−0.377	0.644	16	−1.109	0.542	9	—	—	—
Wt of disc scollop	—	—	—	0.501	0.312	16	0.348	0.368	9	—	—	—
No. of ret red mullet	—	—	—	—	—	—	—	—	—	−1.012	0.833	12
Wt of ret red mullet	—	—	—	—	—	—	—	—	—	−0.345	0.632	12
No. of ret rsw	—	—	—	0.893	0.194	14	—	—	—	—	—	—
Wt of ret rsw	—	—	—	1.270	0.113	14	—	—	—	—	—	—
No. of disc rsw	—	—	—	4.911	**0.0001**	16	3.593	**0.004**	8	3.704	**0.001**	15
Wt of disc rsw	—	—	—	4.574	**0.0002**	16	2.554	**0.019**	8	3.979	**0.0007**	15
No. of disc sw	—	—	—	—	—	—	2.776	**0.011**	10	2.958	**0.005**	16
Wt of disc sw	—	—	—	—	—	—	2.566	**0.015**	10	3.077	**0.004**	16
No. of disc john dory	2.611	**0.012**	12	—	—	—	—	—	—	—	—	—
Wt of disc john dory	3.174	**0.004**	12	—	—	—	—	—	—	—	—	—
No. of disc ebs	—	—	—	—	—	—	−1.139	0.862	14	−1.037	0.842	16
Wt of disc ebs	—	—	—	—	—	—	−0.919	0.812	14	−0.971	0.826	16
No. of ret tiger flathead	−0.349	0.634	13	—	—	—	—	—	—	—	—	—
Wt of ret tiger flathead	−0.602	0.721	13	—	—	—	—	—	—	—	—	—
No. of disc tiger flathead	1.282	0.111	14	—	—	—	—	—	—	—	—	—
Wt of disc tiger flathead	1.71	0.055	14	—	—	—	—	—	—	—	—	—
No. of disc redfish	0.947	0.179	15	—	—	—	—	—	—	—	—	—
Wt of disc redfish	−0.131	0.551	15	—	—	—	—	—	—	—	—	—
No. of leatherjacket	—	—	—	—	—	—	—	—	—	2.404	**0.014**	16
Wt of leather jacket	—	—	—	—	—	—	—	—	—	2.15	**0.024**	16
No. of red bigeye	—	—	—	—	—	—	3.344	0.002	16	2.528	**0.012**	15
Wt of red bigeye	—	—	—	—	—	—	4.122	0.0004	16	2.548	**0.012**	15
No. of flutefish	—	—	—	1.841	**0.045**	13	—	—	—	—	—	—
Wt of flutefish	—	—	—	1.851	**0.044**	13	—	—	—	—	—	—
No. of blackeyes	4.364	**0.0003**	16	—	—	—	—	—	—	—	—	—
Wt of blackeyes	5.459	**0.0001**	16	—	—	—	—	—	—	—	—	—
No. of gurnard	—	—	—	—	—	—	—	—	—	2.392	**0.018**	15
Wt of gurnard	—	—	—	—	—	—	—	—	—	2.034	**0.033**	15
No. of disc comm sp	1.168	0.1306	16	−2.282	0.981	16	0.436	0.334	16	−0.674	0.744	16

cant differences detected in the size-compositions of stout whiting at Yamba (Fig. 6A); however, at Ballina, the control codend caught proportionally more small stout whiting than the composite-panel codend (Fig. 6B).

Discussion

This study has shown the effectiveness of square-mesh panels in allowing nontarget organisms to es-

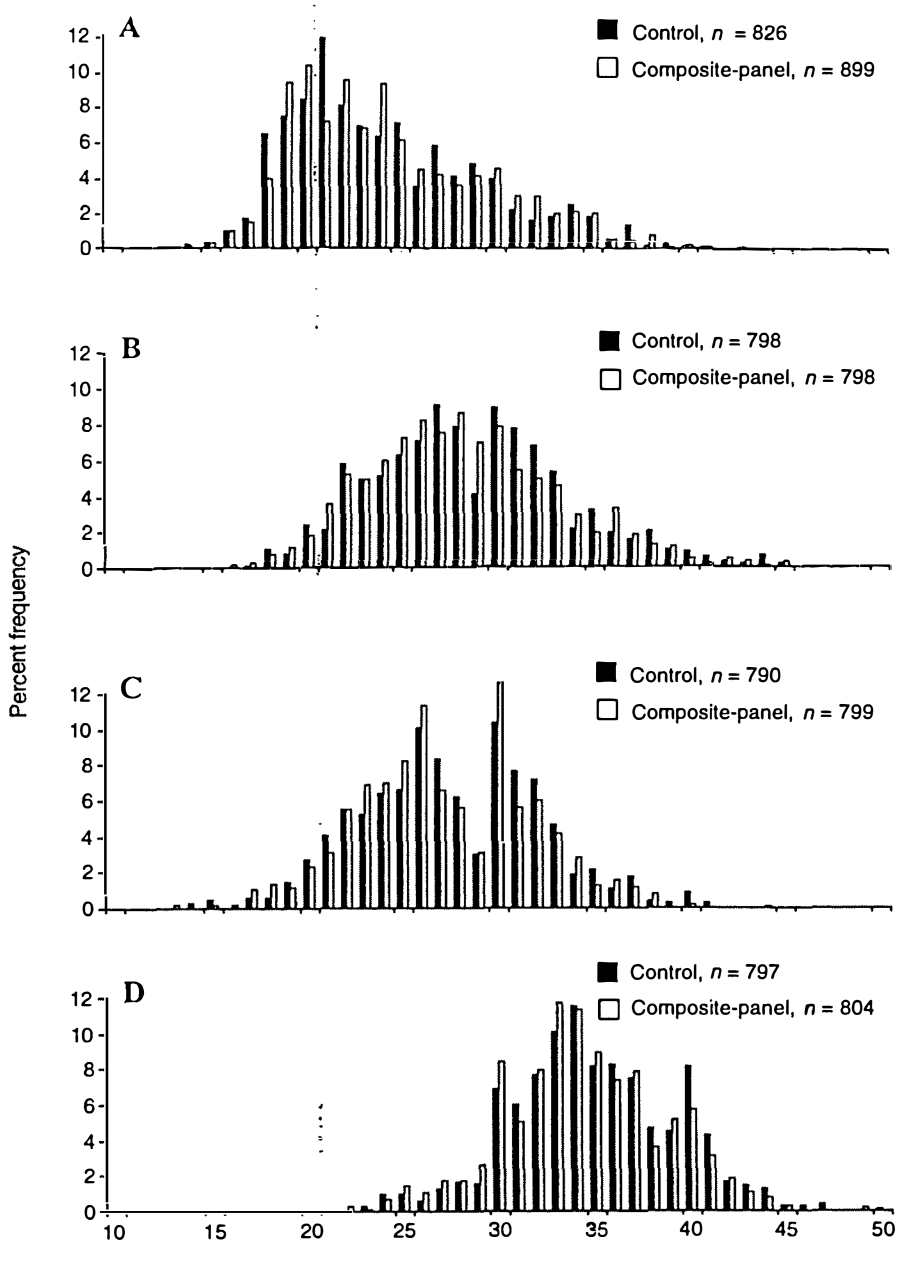

Figure 4
Size-frequency distributions of king prawns caught with control and composite-panel codends from (**A**) Port Stephens, (**B**) Southwest Rocks, (**C**) Yamba, and (**D**) Ballina.

cape trawls (see also Briggs, 1992; Fonteyne and M'Rabet, 1992; Broadhurst and Kennelly, 1994, 1995, 1996; Broadhurst et al., 1996) while maintaining catches of commercially important species. By conducting independent experiments on different vessels across four ports over a range of fishing conditions and catches, we have also provided information on the relative performance of the composite-panel throughout the full operational range of the NSW oceanic prawn-trawl fishery and have documented, for the first time, a significant increase in the catch of targeted prawns with this design.

The composite-panel codend was most effective in excluding large quantities of those discarded species that are relatively fusiform and of a size small enough to pass through the square-meshes. Species such as

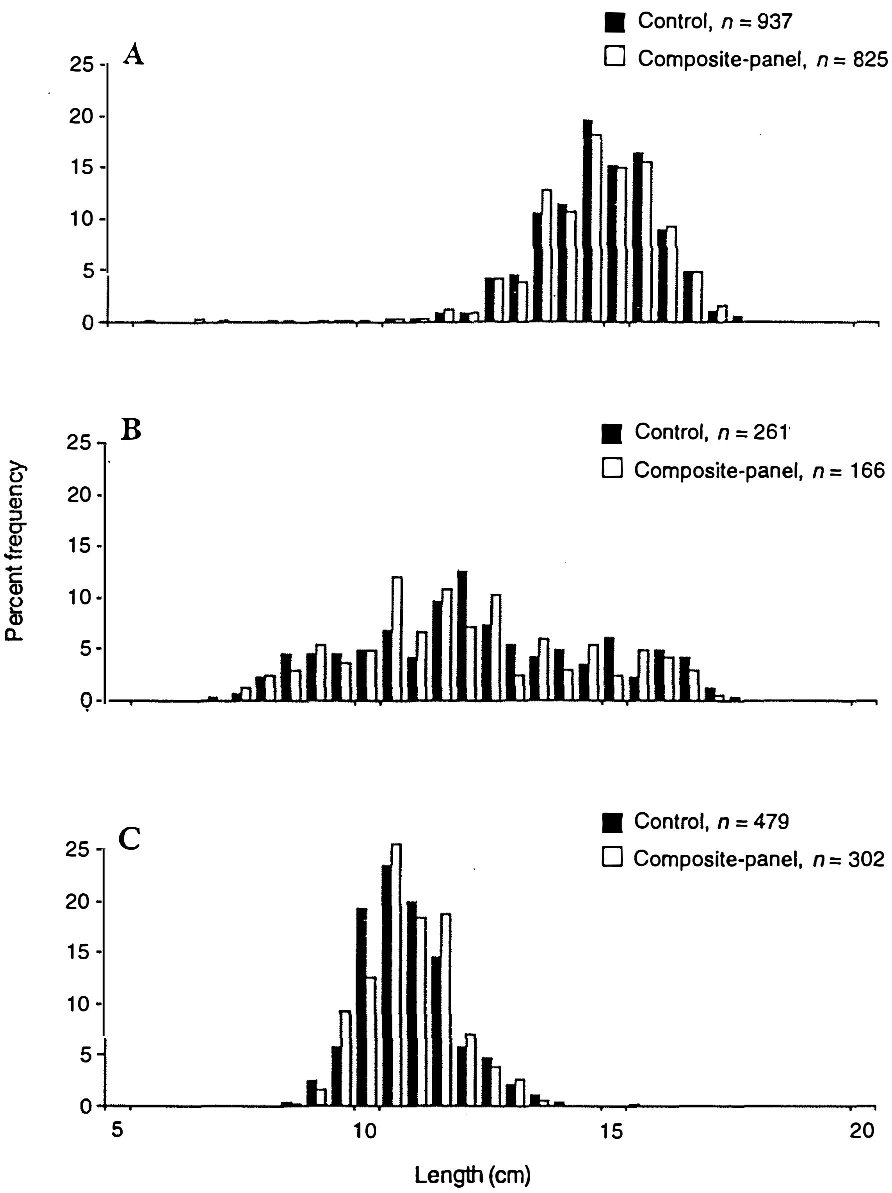

Figure 5

Size-frequency distributions of discarded red spot whiting caught with control and composite-panel codends from (A) Southwest rocks, (B) Yamba, and (C) Ballina.

blackeyes, flute fish, red bigeye, and, in particular, stout and red spot whiting, were all significantly reduced by the composite-panel, which contributed towards a reduction in the mean weight of discarded bycatch at all locations from 23.5% to 41% (Fig. 3). Assuming minimal differences between the various vessels and their gear, the relative availability of these fusiform species throughout waters off New South Wales may explain the variations in the mean reductions of total discarded bycatch at each of the ports and across the fishery. For example, there were no red spot or stout whiting captured at Port Stephens (Fig. 3, E–G), and there was only a 23.5% reduction in total discarded bycatch by the composite-panel at that location (Fig. 3B). In contrast, the discarded bycatch at Yamba and Ballina included large numbers of whiting and red bigeye (up to 500 fish and 1,000 fish, respectively, from each tow in the control net) (Fig. 3, E–F and K) and correspondingly large percentage reductions in total discarded bycatch (41% and 39.5%, respectively) (Fig. 3B).

The above reductions in total discarded bycatch with the composite-panel provide a possible explanation for the significant increase in catches of

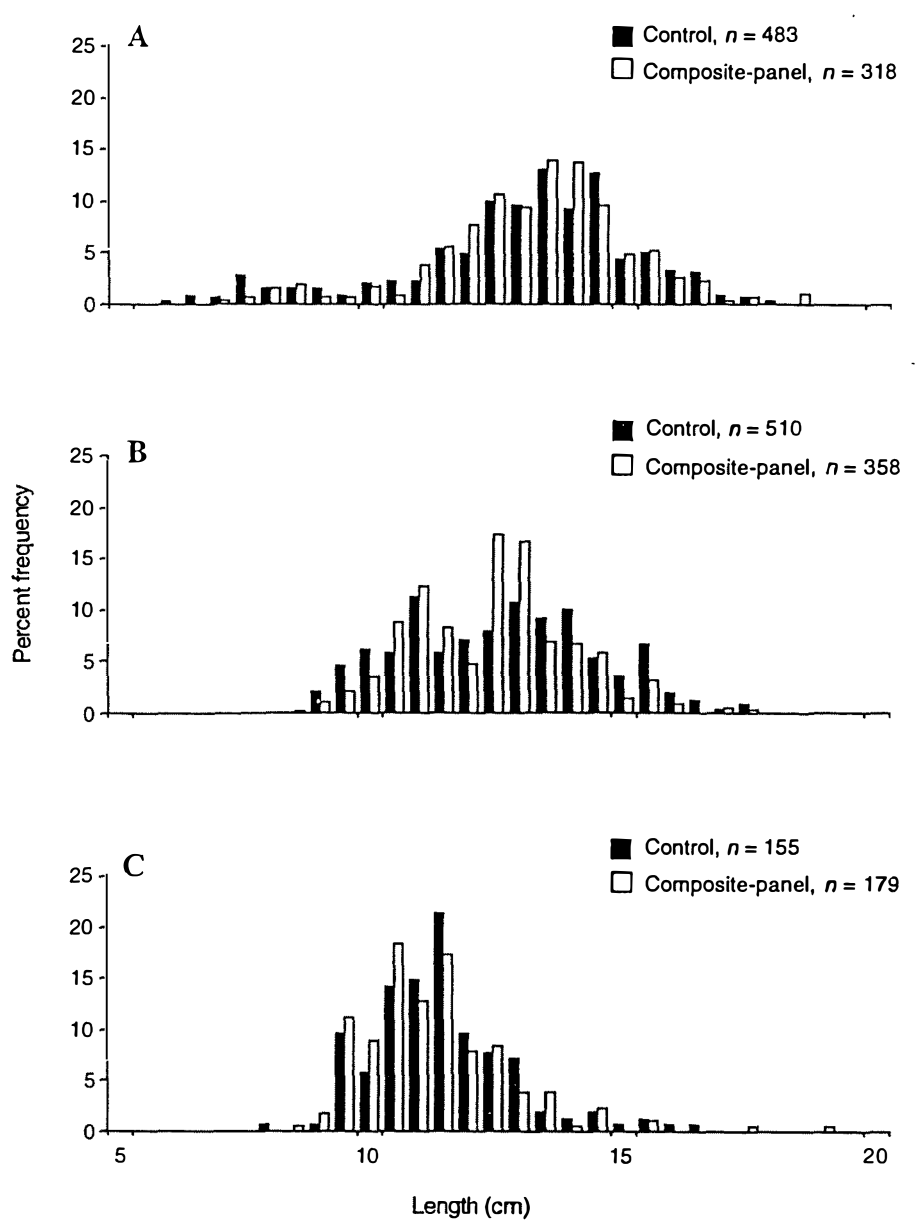

Figure 6

Size-frequency distributions of discarded stout whiting caught with control and composite-panel codends from (**A**) Yamba, (**B**) Ballina, and (**C**) size-frequency distributions of retained red mullet from Ballina.

prawns at Port Stephens, Yamba, and Ballina (by 14%, 5.5%, and 6%, respectively) and for the nonsignificant increase of 4% at Southwest Rocks (Fig. 3A). By reducing the amount of total discarded bycatch and therefore the weight and drag in the codend, the trawl with the composite-panel may have achieved greater spreads between the otter boards (i.e. an increased swept area) than did the control, thereby covering more of the seabed and capturing more prawns. These prawns were probably the same sizes as those that we sampled, because Kolmogorov-Smirnov tests failed to detect any significant differences in prawn sizes between the codends for any of the ports (Fig. 4).

In support of the theory discussed above, there was also an increase (although not statistically significant) in the mean numbers of retained octopus at Southwest Rocks and Yamba (by 11% and 14%, respectively), retained red mullet (by 17%) at Ballina, and discarded eastern blue spot flathead at Yamba and Ballina (by 19.5% and 14.5%, respectively) with the composite-panel (Fig. 3, C–D, and I; Table 1).

Given the physical profile of these individuals and their large size, it is unlikely that once captured by the trawl, they would have been able to fit through the small square-meshes of the composite-panel. In a previous study (Broadhurst and Kennelly, 1996), we showed that large quantities of small individuals of long spined flathead, *Platycephalus longispinis*, escaped through the square-meshes in the composite-panel (62% reduction compared with a conventional codend). Because the tiger and eastern blue spot flathead captured in the present study are physically similar to this species, it may be possible to facilitate their escape simply by increasing the size of mesh in the panel (assuming they display similar responses to stimuli from the trawl). Such a modification, however, would likely result in less retention of smaller individuals of commercially important species such as red spot and stout whiting (see Figs. 5 and 6, A–B), cuttlefish, and southern calamari. In addition, the composite-panel has been designed so that the load is distributed across the many bars of the 40-mm square-shaped mesh. Any major increase in this mesh size would result in the distribution of load across fewer bars, possibly altering the geometry of the codend and its overall performance.

In the present study, we have shown that the composite-panel codend consistently increased catches of prawns over a range of operational conditions while removing large quantities of unwanted bycatch throughout the entire geographic range of the NSW oceanic prawn-trawl fishery. In another study in Australia, Robins-Troeger et al. (1995) tested a large and comparatively complex BRD (termed the "AusTED") off northern Australia and, despite reports of significant losses of prawns, concluded that "the AusTED system has the potential to be developed to suit trawling conditions encountered in different Australian prawn fisheries." It is unlikely, however, that any design of a BRD would be accepted and endorsed by fishermen if it did not consistently maintain catches of the target species throughout the range of the fishery—as is shown to be the case in the present paper for the composite-panel codend (see also Kendall, 1990; Renaud et al., 1992).

In terms of promoting a large-scale voluntary adoption of BRD's, like the composite-panel described in the present paper, it is useful to provide industry not only with evidence of catch rates similar to those obtained with conventional gear but also with evidence of additional benefits, such as a potential for increasing duration of tows, improving quality of catches (due to less damage from bycatch in the codend), increasing savings in labor and fuel, reducing sorting times, and reducing conflicts with other user groups (e.g. recreational and commercial fishermen targeting stocks of bycatch species). The realization of these incentives, along with the results from the present study, have resulted in many commercial fishermen using the composite-panel throughout the entire NSW oceanic prawn-trawl fishery.

Acknowledgments

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Simulated escape of juvenile sand whiting (*Sillago ciliata*, Cuvier) through square-meshes: Effects on scale-loss and survival

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Abstract

Two laboratory experiments were done to assess effects of simulated escape through square-meshes on the scale-loss and survival of (i) non-fatigued and (ii) fatigued small sand whiting (*Sillago ciliata*). In experiment 1, non-fatigued fish that were forced through square-meshes (treatment fish) showed no significant difference in scale-loss compared to fish that did not pass through square-meshes (control fish), although there was a 50% difference in mean scale-loss immediately posterior to their maximum height. In experiment 2, fish were fatigued to exhaustion by swimming against a current of 0.7 to 0.8 knots for 15 min. Fatigued fish that were then forced through square-meshes showed significantly more scale-loss across their entire body than did the fatigued control fish (difference in means of between 67% to 84%). In both experiments the total scale-loss on treatment fish was quite low (1.4–4%) and there were negligible mortalities (only 2 treatment fish died in experiment 1) over the duration of each experiment (30 days). We conclude that the composite square-mesh panel currently used to reduce by-catch in the NSW oceanic prawn trawl fishery is likely to cause negligible damage and mortality of small sand whiting. © 1997 Elsevier Science B.V.

Keywords: Scale-loss; Survival; By-catch reduction; Square-mesh panel; *Sillago ciliata*

1. Introduction

In New South Wales, Australia, oceanic prawn-trawling occurs from 9 major oceanic ports and is valued at ca. A$17 million per annum (1990–91). Although vessels working in this fishery predominantly target the eastern king prawn, a significant proportion of the total value of the fishery is derived from the sale of legally retained by-catch, comprising several species of fish, crustaceans and cephalopods. However, like the majority of the world's prawn-trawl fisheries, significant numbers of non-target organisms are caught incidentally with the targeted species (for reviews see Saila, 1983; Andrew and Pepperell, 1992; Alverson et al., 1994; Kennelly, 1995). In NSW, this by-catch often includes a large assemblage of small fish, some of which are juveniles of commercially and recreationally important species (Kennelly, 1995). The incidental capture and mortality of large numbers of these species is perceived as a negative impact of prawn-trawling because it may reduce the potential biomass and yield of recruited stocks (see also Gulland, 1973; Howell and Langan, 1987).

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To address these concerns in NSW, Broadhurst et al. (1996) and Broadhurst and Kennelly (1996) developed and assessed several designs of by-catch reducing devices (BRDs), that incorporated panels of square-shaped mesh located in the top anterior sections of prawn-trawl codends. In particular, a new design comprised of composite panels of square-shaped mesh (referred to as the composite square-mesh panel codend) was shown to be effective in reducing up to 40% of the total unwanted by-catch and up to 70% of the numbers of juveniles of species such as whiting (*Sillago* spp.) while maintaining catches of prawns.

The results from these experiments led to the voluntary adoption of this design by many fishers operating in the NSW oceanic prawn-trawl fishery. Such widescale application should, therefore, directly alleviate some of the perceived negative effects of prawn-trawling discussed above by reducing the by-catch landed onboard vessels. However, without estimates of the numbers of fish that survive after escaping these trawls, it is difficult to quantify the longer-term benefits that this device may have on subsequent stocks of these species.

Several methods have been used in previous studies to determine the damage and mortality incurred by fish as they pass through meshes. One approach has been by direct observations employing video or SCUBA to assess effects (Main and Sangster, 1988; Suuronen and Millar, 1992; Suuronen et al., 1996a). Unfortunately, because trawling in NSW's oceanic prawn trawl fishery often occurs in deep water with poor visibility, or at night, and sometimes in rough conditions, this method was impractical.

Another approach involves encompassing the codend and BRD in a fine-meshed cover or cage that retains any fish which escape (Soldal et al., 1993; Suuronen et al., 1995a, 1996a; Sangster et al., 1996). At the end of a short towing period, these covers are sealed, released and anchored, providing a group of 'treatment fish' to be compared against 'control fish', which are usually caught using some alternative method (e.g., by hook and line, see Sangster et al., 1996; Suuronen et al., 1996b). Such experiments have the advantage of being done under the actual conditions in which species escape. However, their very large cost combined with inherent variabilities among tows in fishing conditions and the distributions of species retained, means that the experiments are difficult to replicate in space and time, and therefore may lack sufficient statistical power to detect effects. Further, it is difficult to provide accurate controls within the experimental design, since the 'control fish' are almost always subjected to some form of stress that differs from 'treatment fish' during their initial capture. In addition, control fish may come from different populations and/or stocks and may have a different overall condition and/or represent different size classes than the treatment fish.

An alternative and simpler method to assess the extent of trawl-induced mortalities is to simulate the escape of fish in a laboratory (e.g., Soldal et al., 1993). Whilst this approach can not fully represent how individual fish are affected during capture and subsequent escape under commercial conditions, it does control many of the confounding effects described above and, with sufficient replication, can provide adequate statistical power. Such experiments, however, require an initial catching method that does not result in significant damage to the subject species.

Our specific goals in this paper were to simulate the trauma incurred by small sand whiting (*Sillago ciliata*, a species common in estuaries throughout NSW) as they pass through square-meshes that are the same size as those in the main escape panel of the composite-panel codend (60 mm netting hung on the bar, see Broadhurst and Kennelly, 1996). For both non-fatigued and fatigued fish, we aimed to quantify: (i) the extent of scale-loss (to provide an estimate of their overall condition); and (ii) their rate of post-trawl mortality.

2. Materials and methods

Two experiments were done at NSW Fisheries Research Institute's aquarium facilities between June and October 1996 using one 4000 l fibreglass holding tank and 22 smaller fibreglass tanks (200 l, see Fig. 1A). All tanks were supplied with seawater (at ambient temperature) at a rate of 1.8 l min^{-1}, aerated using air-stone diffusers and equipped with outflow pipes (termed 'stand-pipes'), designed to maintain constant water levels. The small tanks were

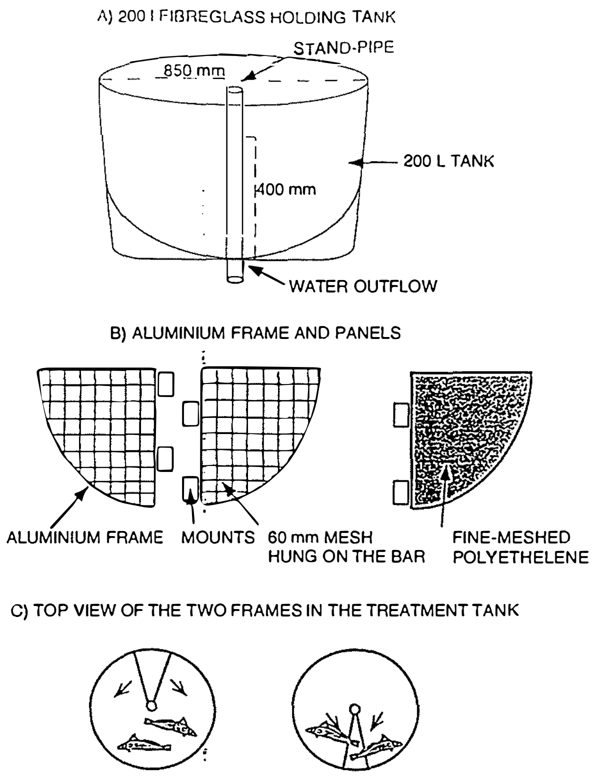

Fig. 1. Diagrammatic representation of: (A) the 200 l fibreglass tanks, (B) the aluminium frames and panels used in the experiments and (C) the frames being rotated together in the treatment tanks (top view).

distributed on opposite sides of an enclosed room and had their stand-pipes located in their centres.

Three identical aluminium frames were constructed so that they could be inserted over each of the stand-pipes in the smaller tanks (Fig. 1B). Two of the frames were rigged with identical panels of 60 mm netting, cut on the bar (the same as that used in the main escape panel of the composite-panel codend, see Broadhurst and Kennelly, 1996). These two panels could be placed along side each other, and rotated freely throughout the entire volume of the tank (Fig. 1C). The third frame was fitted with a panel of fine-meshed polyethylene (mesh size 2 mm) (Fig. 1B).

2.1. Collection of fish for experiments

Approximately 560 juvenile sand whiting (< 20 cm) were captured in Port Hacking (34° 47′S, 151° 8′E) adjacent to NSW Fisheries Research Institute using a seine net (mesh size 15 mm). After capture, fish were carefully removed from the net, placed in a holding tank in the boat (400 l, stocking density of < 5 kg fish m^{-3}) at ambient temperature and supplied with pure oxygen. These fish were transported to the aquarium facility at the Fisheries Research Institute and transferred (using buckets) to the 4000 l holding tank. To reduce the possibility of infection arising from initial capture, a mixture of 100 mg l^{-1} of Oxytetracycline was added and water flow was stopped for 6 h.

The fish were allowed to acclimatise in the large holding tank for a period of 14 days, during which time they were fed a diet of chopped pilchards (at a rate of 1% biomass per day) and any dead fish were removed immediately and recorded. Any faeces and uneaten food that settled in the tanks were removed daily by siphoning.

2.2. Experiment 1: Effects on non-fatigued fish due to passing through square-meshes

On the 15th day, all fish were anaesthetised using benzocaine (ethyl-*p*-aminobenzoate, 50–75 mg l^{-1} in sea water, see also Quartararo and Bell, 1992). 330 fish were selected at random, individually checked for any signs of scale-damage (any damaged fish were left in the holding tank), removed (using buckets filled with water) and then placed in groups of 15 into the 22 smaller tanks. These fish were fed and monitored (using the methods outlined above for the holding tank) and left to acclimatise for a further 10 days. At the end of this second acclimatising period, 18 of the tanks were designated at random as either treatments or controls (9 of each). Fish in the remaining 4 tanks (stock tanks) were used to replace any mortalities in the treatment and control tanks (to maintain constant stocking densities throughout the experiment).

On day one of experiment 1, the two aluminium frames with panels of square-mesh were placed in each of the treatment tanks. These frames were rotated around the tanks in opposite directions at approximately 0.5 m s^{-1}, so that fish were herded together and forced to swim through either of the panels containing the square-mesh (Fig. 1C). In each of the control tanks, the aluminium frame containing the fine-meshed polyethylene was used to herd fish once around the tank. These fish were herded like the treatment fish but did not come in contact with any mesh.

The treatment and control tanks were divided at random into two groups: Group 1 contained 4 treatment and 4 control tanks and was used to assess scale-loss. Group 2 contained 5 treatment and 5 control tanks and was used to assess total mortalities.

2.3. Experiment 2: Effects on fatigued fish due to passing through square-meshes

Two months after their initial capture, 240 fish in the 4000 l holding tank were anaesthetised according to the methods described in experiment 1. Two hundred and twenty fish were individually checked for any signs of scale-damage, removed and placed in the smaller tanks in groups of 10. These fish were left to acclimatise for 21 days. At the end of this period the tanks were designated according to the classification provided in experiment 1 (9 treatment tanks, 9 control tanks and 4 stock tanks).

On day 1 of experiment 2, the stand-pipes were removed in each treatment and control tank and replaced with a 12 V submersible water pump (Fig. 2). A cylinder of PVC (250 mm dia × 600 mm long) was then fitted over the pump (Fig. 2) which (i) prevented fish from physical contact with the pump

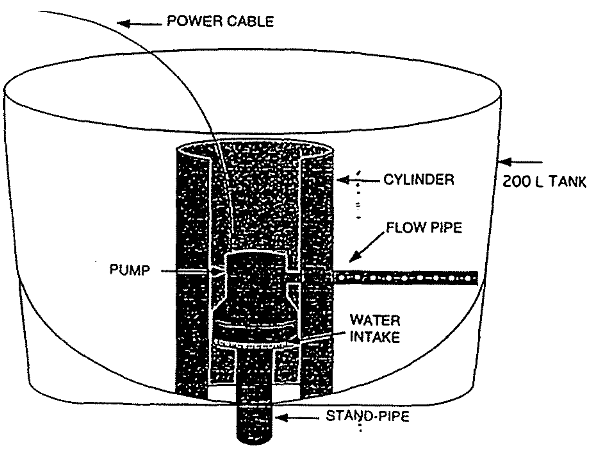

Fig. 2. Diagrammatic representation of the submersible pump assembly used in experiment 2.

and (ii) concentrated fish into a smaller volume of water. The pump was activated for 15 min, producing a circulating water flow of between 0.7 and 0.8 knots within each of the tanks (flow was measured at several positions using an electromagnetic current meter). During this period, the fish were observed to orientate towards the direction of flow and attempt to maintain station until exhausted (approximately 10 min for most fish). Fatigued fish drifted back with the flow and made little attempt to maintain position relative to the tank. We intended this treatment to simulate the exhaustion incurred by fish as they are caught in the trawl.

At the end of 15 min the pump and PVC cylinder were removed from the tank and the stand-pipe replaced. Depending on the classification of each tank (i.e., treatment or control) the respective aluminium frames were inserted and used according to the methods described in experiment 1 (Fig. 1C). Because two fish jumped out of the tanks during experiment 1 (see below), after the aluminium frames were removed in experiment 2, flexible mesh covers were placed over each of the tanks.

As was the case in experiment 1, the treatment and control tanks were divided at random into two groups: Group 1 contained 4 treatment and 4 control tanks and was used to assess scale-loss. Group 2 contained 5 treatment and 5 control tanks and was used to assess total mortalities.

2.4. Analysis of scale-loss

Every second day after the start of each experiment, fish in each tank from group 1 were anaesthetised using benzocaine (as described above). Two fish were randomly selected from each tank and carefully removed (using gloves and firmly holding each fish by the head and tail) and killed in a solution of benzocaine (100 mg l^{-1} in sea water). These fish were measured (to the nearest 0.5 cm) and placed ventrally on clear plastic sheets inscribed with silhouettes of fish (the same length and width as each of the samples) divided into five zones per flank (Fig. 3). Using the method described in Main and Sangster (1988), both sides of each fish were visually subdivided and the percentage scale-loss calculated (to the nearest 10%) for each of the five zones on both flanks. The means of these 10 values

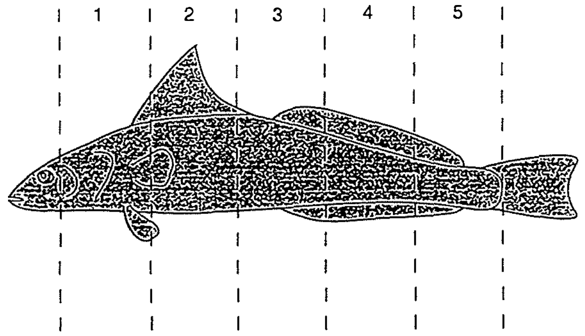

Fig. 3. Fish profile and zones used to estimate scale-loss.

were calculated to provide estimates of the total scale-loss for each fish (see also Main and Sangster, 1988). Using dial callipers, measurements were then taken on the maximum height and width (to the nearest 0.5 mm) and the weight of each fish to determine the likelihood of each fish being able to pass through the 30 mm openings in the square mesh panel.

Data for all variables (i.e., percentage scale-loss per zone and combinations of various zones) were analysed using Cochran's test for homogeneity of variances, and then analysed in the appropriate three-factor analyses of variance (Underwood, 1981). Days and treatment of fish were considered fixed factors in these analyses, tanks were random and the two random fish per tank per observation-day (7 days in experiment 1 and 5 days in experiment 2) were the replicates. Tanks were nested in the treatment of fish.

Two-sample Kolmogorov–Smirnov tests ($P = 0.05$) were used to compare the size frequencies of treatment and control fish within each experiment and aggregated size-frequencies of fish between experiments. The relationships between length and maximum height and width were plotted to determine the likelihood that fish were physically able to pass through the square mesh panel.

2.5. Analysis of total mortality

Fish in group 2 in both experiments were monitored daily for any mortalities over a period of 30 days. All dead individuals were immediately removed from their tanks and replaced with the same number of live fish (which had a small section of caudal fin removed for identification) from a stocking tank. Dead fish were analysed for scale-loss as per the methodology described above. Because a total of only 2 fish died in both experiments, no formal statistical analyses were done on these data. Instead, data from the dead fish are presented in tabular form.

3. Results

3.1. Collection of fish for experiments

18 juvenile whiting, representing approximately 3% of the 560 fish captured by the small meshed seine net, died during the first 14 days in the 4000 l tank. There were no other mortalities during the acclimatising periods in the 200 l tanks.

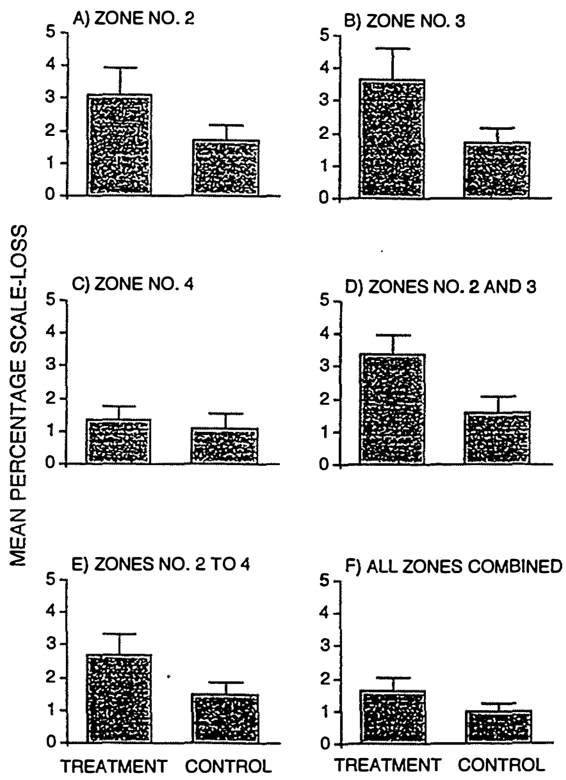

Fig. 4. Differences in mean percentage scale-loss (±SE) between the control and treatment fish in experiment 1 for: (A) zone No. 2, (B) zone No. 3, (C) zone No. 4, (D) zones 2 and 3 combined, (E) zones 2 to 4 combined and (F) all zones combined.

Table 1
Experiment 1: Summaries of F ratios from analyses of variance to determine effects on scale-loss from sand whiting due to different treatments of fish (i.e., control vs. those fish that had passed through the square-meshes), days and tanks[a]

Treatment	d.f.	Zone No. 2 $\ln(x+1)$	Zone No. 3 $\ln(x+1)$	Zone No. 4	Zones No. 2 and 3 combined $\ln(x+1)$	Zones No. 2 to 4 combined $\ln(x+1)$	All zones combined
Days (D)	6	1.01	0.78	1.49	1.01	1.14	1.46
Treatment of fish (TF)	1	1.99	3.20	0.19	3.77	2.95	2.03
Tanks (T)	6	1.06	0.63	0.94	0.91	0.52	0.51
$D \times$ TF	6	1.12	0.64	1.13	0.58	0.72	1.25
$D \times T$	36	1.26	1.43	1.18	1.61	1.46	1.03
Residual	54						

[a] The transforms used to stabilise variances (if required) are listed. Insufficient replication due to one fish missing from a control and treatment tank required the inclusion of the cell mean and 2 d.f. were subtracted from residual d.f.
** Significant ($P < 0.01$); * Significant ($P < 0.05$).

3.2. Experiment 1: Effects on non-fatigued fish due to passing through square-meshes

3.2.1. Scale-loss

There were no mortalities of fish in group 1 (the scale-loss group) that were attributable to passing through the square-mesh, however, one fish managed to jump out of a control tank and one out of a treatment tank. There were no significant differences nor interactions detected in experiment 1. Although non-significant, there was a mean increase in scale-loss in zone No. 3 (54% difference in means) and in zones 2 and 3 combined (50% difference in means) for fish that had passed through square meshes compared to fish from the control tanks (Fig. 4B,D and Table 1) and similar trends (as above) in the differences in mean scale-loss in each zone and combinations of zones (from 20% to 46.8%) (Fig. 4 and Table 1).

3.2.2. Total mortality

Two fish escaped from the tanks in group 2 in experiment 1, one from a control tank and one from a treatment tank. Two fish in the treatment tanks died 9 and 10 days, respectively, after they passed through the square-meshes (see Table 2), resulting in a total survival rate of 97% of fish from group 2. There were no mortalities of fish in the control tanks.

3.3. Experiment 2: Effects on fatigued fish due to passing through square-meshes

3.3.1. Scale-loss

There were no mortalities of fish in group 1, experiment 2 that were attributable to passing through the square-mesh, although one fish managed to jump out of a treatment tank. Compared to the fish from the control tanks, there was significantly more scale-

Table 2
Summary of the morphology and scale-loss of the two fish that died in the treatment tanks in group 2, experiment 1

Fish. No.	Weight (g)	Width (cm)	Height (cm)	Length (cm)	Percentage scale loss for each zone										
					Left flank					Right flank					
					1	2	3	4	5	1	2	3	4	5	Total
1	21.3	1.5	2.2	14	0	0	0	10	0	0	0	0	0	0	1
2	26.7	1.6	2.5	15	0	0	0	0	0	0	20	30	0	0	5

Table 3
Experiment 2: Summaries of F ratios from analyses of variance to determine effects on scale-loss from sand whiting due to different treatments of fish (i.e., control vs. those fish that passed through the square-meshes), days and tanks[a]

Treatment	d.f.	Zone No. 2 sqrt($x+1$)	Zone No. 3	Zone No. 4 ln($x+1$)	Zones No. 2 and 3 combined	Zones No. 2 to 4 combined	All zones combined
Days (D)	4	0.33	0.36	0.34	0.37	0.43	0.64
Treatment of fish (TF)	1	10.69**	26.11**	4.66*	24.71**	26.74**	26.4**
Tanks (T)	6	1.90	0.72	1.67	0.93	0.66	0.67
$D \times$ TF	4	0.67	1.45	2.81	1.36	1.64	2.03
$D \times T$	24	1.06	1.02	0.47	1.01	1.98	0.85
Residual	39						

[a] The transforms used to stabilise variances (if required) are also listed. Insufficient replication due to one fish missing from a treatment tank required the inclusion of the cell mean and 1 d.f. was subtracted from residual d.f.
** Significant ($P < 0.01$); * Significant ($P < 0.05$).

loss for all zones and combinations of zones for fish from the treatment tanks (differences in means of between 67% and 84%, Fig. 5 and Table 3). There were no other significant differences or interactions detected in experiment 2.

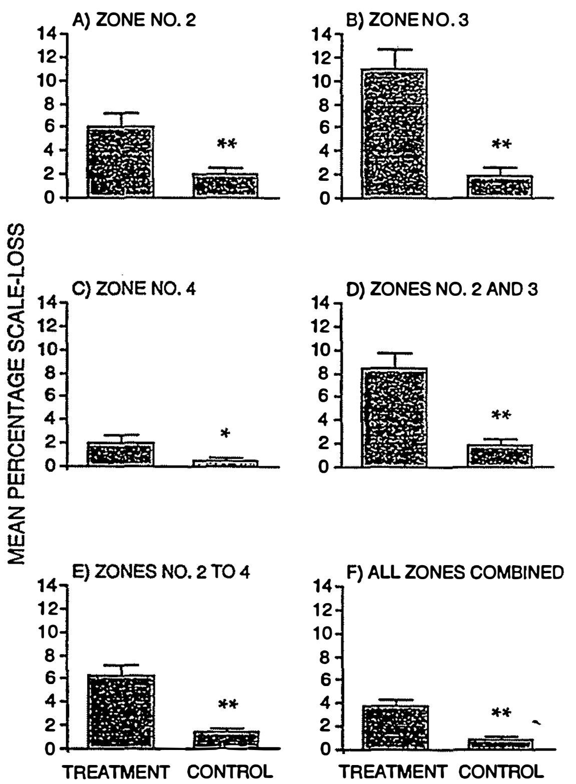

Fig. 5. Differences in mean percentage scale-loss (± SE) between the control and treatment fish in experiment 2 for: (A) zone No. 2, (B) zone No. 3, (C) zone No. 4, (D) zones 2 and 3 combined, (E) zones 2 to 4 combined and (F) all zones combined. ** significant at $P < 0.01$; * significant at $P < 0.05$.

3.3.2. Total mortality

There were no mortalities in group 2 during experiment 2.

3.4. Analysis of size-frequencies, length-height and length-width data from both experiments

Two-sample Kolmogorov–Smirnov tests comparing the size-frequency distributions of fish measured showed no differences between treatment and control tanks within each experiment, but detected differences between experiments (Fig. 6). The fish used in

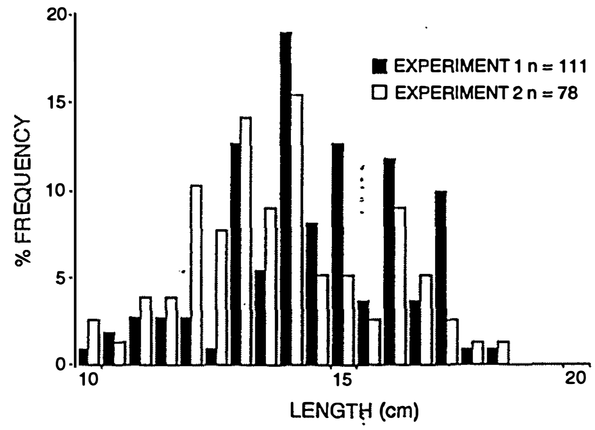

Fig. 6. Size-frequency distributions of sand whiting from experiments 1 and 2.

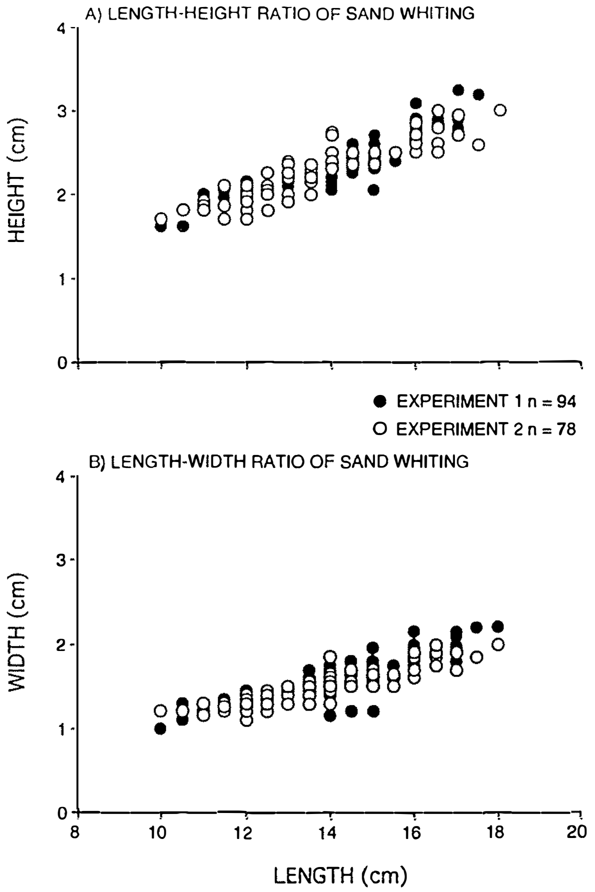

Fig. 7. Relationship between: (A) Length and maximum height and (B) length and maximum width for sand whiting used in the experiments.

experiment 2 were proportionally smaller than those in experiment 1.

The plots of length and maximum height and width for fish from treatment and control tanks showed that most fish easily passed through the square-mesh panel in both experiments (Fig. 7).

4. Discussion

The results from this study showed that the simulated escape of sand whiting through square-shaped meshes had minimal effect on their overall condition and mortality (< 3%). In experiment 1, although non-significant, for non-fatigued fish there were differences in the mean percentage scale loss between treatment and control fish across all zones, particularly zone No. 3 (immediately posterior to the maximum height of the fish) and zones 2 and 3 combined. However, the actual mean percentages of scale-loss in each of the treatment fish were quite low (i.e., a total combined mean scale-loss of 1.7%). Further, the detection of some scale-loss from the control fish (total combined mean scale-loss of 0.9%, probably due to interactions with other fish or movement around the tank), implied that the effects of the square-mesh panel on non-fatigued fish were not significantly greater than the effects of confinement within the tanks.

The results from experiment 2 showed that fatigued fish sustained significantly more damage than non-fatigued fish after passing through square-meshes across all zones (particularly zone No. 3) and combinations of zones (up to 84% difference in means between treatments and controls, Fig. 5). However, like the results from experiment 1, the total average percentage scale-loss from these treatment fish was still quite low (< than 4%, Fig. 5F) and evidently not sufficient to result in any mortality.

Given that the maximum opening of the mesh in the 60 mm square-mesh panel was 30 mm (see Fig. 1B), the length and maximum height and width correlations in Fig. 7 indicate that most of the sand whiting used in both experiments should have easily passed through these meshes. That is, the length-height correlation in Fig. 7A showed that a sand whiting 18 cm in length had a proportionate maximum height of approximately 3 cm, the same size as the maximum mesh opening. Further, the maximum width of a sand whiting 18 cm long was less than the 3 cm maximum mesh opening (i.e., 2.5 cm, see Fig. 7B). However, it is evident from the results in both experiments that several fish of all sizes had contact with the mesh during their simulated escape. The large difference in mean percentage scale loss between treatment and control fish for zone No. 3 in experiment 1 and the significant difference detected in zone No. 3 in experiment 2 (see above and Fig. 4BFig. 5B) suggests that this contact primarily occurred immediately posterior to the point of maximum height of these fish.

These results partly support those from a previous field study in the North Atlantic (Main and Sangster, 1988) which showed that several species of gadoid fish passing through different sizes of mesh, incurred more scale-damage posterior to their widest girth. It was noted, however, that this damage increased progressively back towards the tail (see also Suuronen et al., 1996a,b). In the present study, we observed that initially most fish were reluctant to pass through the mesh and approached slowly, but as they moved through, they initiated several rapid beats of their tails to 'escape' the mesh. This behaviour may have resulted in some contact along their flanks and posterior to their maximum height.

The methodology used in the present study allowed us to assess the damage and mortality incurred by sand whiting after passing through square meshes but did not allow an assessment of other effects like interactions that escapees may have with other by-caught species nor effects incurred as they make contact with the main body of the trawl net (i.e., abrasions, chaffing, etc.). In addition, because the panel used in this laboratory study was positioned vertically, fish probably passed through the square-meshes at a greater angle (i.e., ca. 90°) than might be expected by fish passing through the horizontally-aligned square-meshes of the composite panel under normal field conditions (i.e., at an angle $< 90°$). As a consequence the fish in this study may have had less contact with the square-meshes and they possibly lost fewer scales that might normally be expected. Nonetheless, the results are comparable with those from previous experiments conducted in the field using commercial gears (see DeAlteris and Reifsteck, 1992; Soldal et al., 1993; Suuronen et al., 1995b). For example, in a field experiment in the Barents Sea, Soldal et al. (1993) found zero mortality of cod (*Gadus morhua*) and minimal mortality (an average of 3.7%) of haddock (*Melanogrammus aeglefinus*) that had escaped from the diamond meshes (135 mm) of a demersal trawl.

It is obvious from other studies, however, that many factors influence the rates of mortality of fish that escape trawls, including differences in trawl nets, methods of operation, duration of tows and species-specific variabilities. It is therefore difficult to interpolate results from different fisheries, although in the majority of published studies (see Chopin and Arimoto, 1995 for review), the mortality rates of fish attributed to stress incurred during capture and escape have been estimated to be relatively low in comparison to the numbers of fish surviving (Main and Sangster, 1990; Main and Sangster, 1991; Suuronen, 1991; Millner et al., 1993; Sangster and Lehmann, 1993; Soldal et al., 1993; Turunen et al., 1994, but see Suuronen et al., 1996a). The results from the present study lead us to a similar conclusion: that sand whiting which escape through the composite square-mesh panel used in prawn trawls off the NSW coast undergo relatively minor damage and experience negligible mortality.

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Specifications for the construction and installation of two by-catch reducing devices (BRDs) used in New South Wales prawn-trawl fisheries

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Introduction

Prawn trawling occurs in five estuaries and from nine major oceanic ports in New South Wales and is valued at approximately $A25 million per annum. Significant numbers of non-target organisms ('by-catch', Saila 1983) are captured, comprising a large and diverse assemblage of small fish, some of which are juveniles of commercially and recreationally important species (Liggins and Kennelly 1996; Liggins *et al.* 1996; Kennelly *et al.* 1997). Concerns over the incidental capture and mortality of large numbers of these juveniles led to the development and assessment of several by-catch reducing devices (BRDs) in prawn-trawls (Broadhurst and Kennelly 1996*a*, 1996*b*, 1997; Broadhurst *et al.* 1996, 1997). These designs were tested in different fisheries in NSW according to species-specific spatial and temporal variabilities in by-catches and the commercial fishing techniques employed. Two of these designs, the 'Nordmøre grid' (Isaksen *et al.* 1992) and the 'composite square-mesh panel' (Broadhurst and Kennelly 1996*a*), significantly reduced by-catch whilst maintaining (and in some cases increasing) catches of the target species. As a result, these devices were subsequently recommended for use in the appropriate fisheries as part of normal commercial operations.

Although the performances of these BRDs are well documented, detailed descriptions of the methods for their construction and installation into commercial prawn-trawls are lacking. Such information is necessary to ensure their efficient operation in maximizing the escape of by-catch while maintaining catches of targeted species during normal commercial operations. Such information is provided here. All terminology used to describe the cutting tapers and orientation of meshes to the general course of netting (e.g. 'normals' or N, bars or B and 'transversals' or T) are based on those described in Anon. (1972).

The Nordmøre grid

The Nordmøre grid functions mainly by partitioning the catch according to size. A guiding funnel or panel located anterior to the codend directs the entire catch to the base of a sorting grid comprising vertically orientated bars (see also Isaksen *et al.* 1992). Prawns and most organisms smaller than the bar spacings in the grid pass through and into the codend, while fish and other larger organisms are directed upwards and out through an opening in the top of the trawl (Fig. 1*a*). In comparisons with standard commercial trawls in NSW estuaries, the Nordmøre grid reduced the mean weight of by-catch by 77–90% and the numbers of juveniles of commercially important species such as bream, *Acanthopagrus australis*, by up to 67% with no significant reduction in the catches of the prawns *Metapenaeus macleayi* and *Penaeus plebejus* (Broadhurst and Kennelly 1996*b*; Broadhurst *et al.* 1996, 1997).

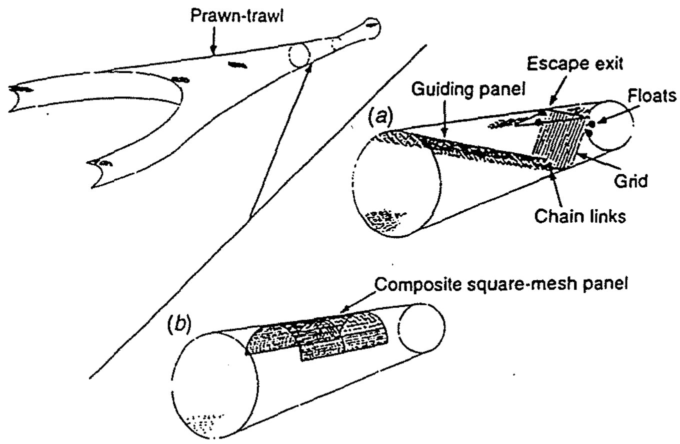

Fig. 1. Diagrammatic representation of a prawn-trawl and location of *(a)* the Nordmøre-grid and *(b)* the composite square-mesh panel.

Construction and installation

The following materials are required for the construction of a Nordmøre grid suitable for most designs of prawn-trawls in NSW with a headline length less than 11 m and a mesh size in the codend of between 40 and 45 mm: *(i)* a section of netting (100 × 100 mesh) of 400/36-ply polyethylene (mesh size 40–45 mm), *(ii)* a 2-m length of round aluminium rod 12 mm in diameter (for the frame), *(iii)* a 7-m length of round aluminium rod 10 mm in diameter (for the bars) and *(iv)* four 100-mm diameter polystyrene floats.

The aluminium rods are cut and welded (Fig. 2) to form the grid. A gap of 20 mm (suitable for penaeid prawns up to 25 mm carapace length) between each bar will require 12 bars and 13 spaces to fill the 400-mm frame.

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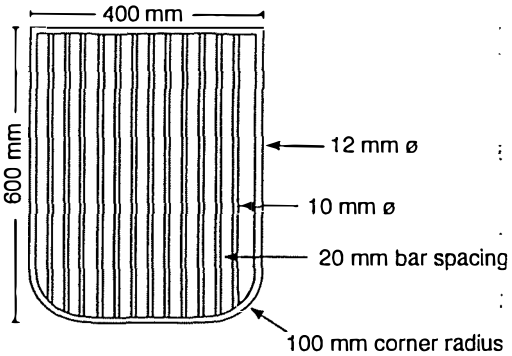

Fig. 2. Aluminium grid used in the Nordmøre-grid (ø, diameter).

Steps for assembling the netting and inserting the grid are as follows.

1. Cut the netting into five panels (Fig. 3*a*): Panel 1 will become the net extension, Panels 2 and 3 will become the guiding panel and Panels 4 and 5 will be reserved for a spare guiding panel.

2. Cut out the triangular escape exit (25 T × 25 B) from Panel 1 (Fig. 3*a*).

3. Sew the anterior edges of Panels 2 and 3 together (Fig. 3*b*). To ensure consistent knot direction of the twine throughout the guiding panel, it is important to 'flip' either Panel 2 or Panel 3 upside-down and back-to-front. The same applies for the spare panels, 4 and 5.

4. Place the guiding panel on top of Panel 1 and sew or lace (mesh for mesh) the anterior edge of the guiding panel to the centre of the anterior edge of Panel 1.

5. With a permanent marker pen, draw dotted lines on Panel 1 (Fig. 3*a*), starting 12 meshes from the centre of the panel and following a 1N 2B taper (see Fig. 3*c*) down the netting, finishing 13 meshes from the outside edges. Sew or lace the meshes at the sides of the guiding panel, row for row, to the marked lines on Panel 1 (the guiding panel will tend to pull quite tightly as the two panels of net are sewn together).

6. Turn up the two outside edges of Panel 1 and sew them together to form a seam that will correspond to the bottom centre-line of the trawl.

7. Insert the aluminium grid into Panel 1 (now attached to the guiding panel) and evenly lace the 25 meshes that form the base of the triangular escape exit to the top edge of the grid (Figs 1*a* and 4).

8. To secure the grid inside the netting at an angle of approximately 45°, follow the row of meshes that forms the base of the triangular escape around the net to the bottom centre-line, measure forward 424 mm (this distance is calculated from the formula 600 mm sin 45°) to a row of meshes and lace the bottom of the grid to at least 15 meshes along that row (Fig. 4).

9. The remaining netting surrounding the sides of the grid between the top and bottom should be evenly laced to the grid. This needs to be done correctly to avoid altering the geometry of Panel 1.

10. The edges of the triangular escape exit should be reinforced by tightly selvedging (binding) to rope (e.g. 10-mm twisted polyethylene rope), which can then be spliced to the corners of the grid to help to support and maintain the correct grid angle of 45°.

11. A few links of light chain (e.g. five links of 6 mm) can be added to the posterior end of the guiding panel (Fig. 1*a*), to reduce lifting and minimize the risk that prawns will escape.

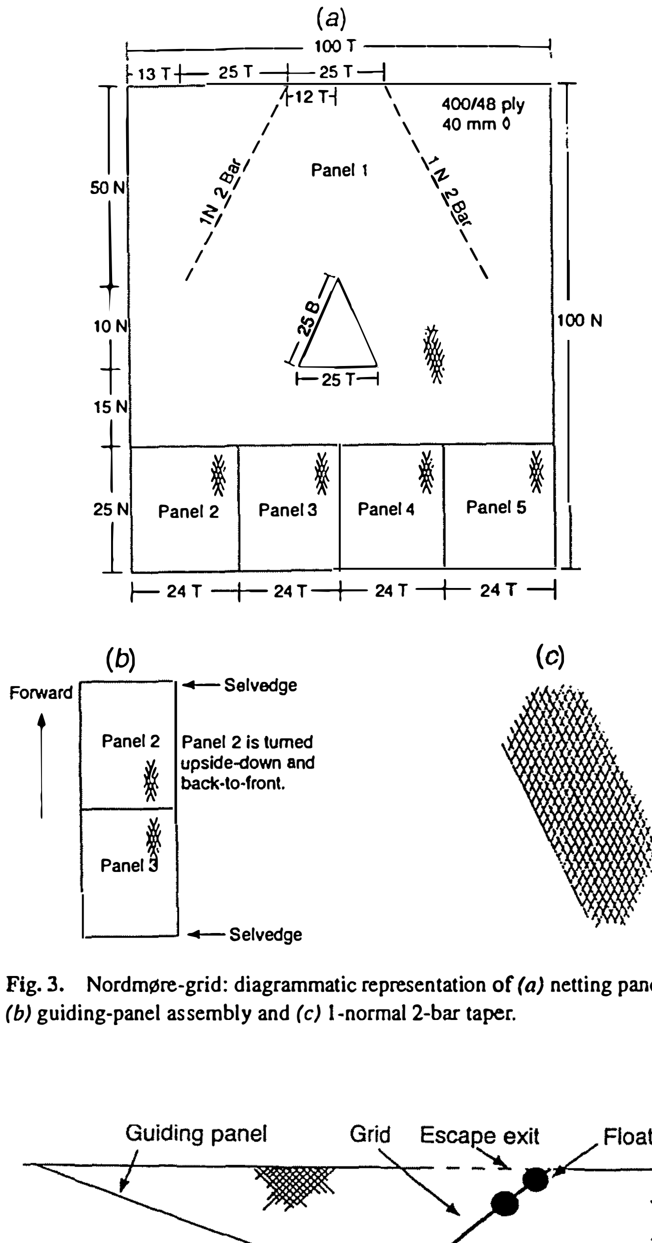

Fig. 3. Nordmøre-grid: diagrammatic representation of *(a)* netting panels, *(b)* guiding-panel assembly and *(c)* 1-normal 2-bar taper.

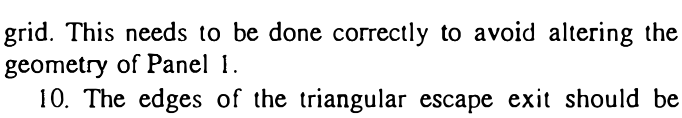

Fig. 4. Side view of completed Nordmøre-grid.

12. The four floats must be attached to the top of the sides of the aluminium grid (to provide a slightly positive buoyancy) (Figs 1*a* and 4).

The entire assembly comprising guiding panel, aluminium grid, floats and escape exit (all attached to Panel 1) can be inserted between the codend and the main body of the net. The line normally used to retrieve the codend (termed 'lazyline', see also Anon. 1972) should be attached to some point anterior to the grid on the bottom of the net extension (Panel 1).

The distance of the posterior end of the guiding panel from the base of the aluminium grid can be adjusted to maximize fish escape while maintaining catches of prawns. For example, fish escape can be improved by removing two or three rows of mesh from the posterior end of the guiding panel and/or reducing the amount of chain. Conversely, if some prawns escape, additional mesh may be attached to the posterior end of the guiding panel (so that it touches the base of the grid) and/or it can be weighted with additional chain. In areas where there are large quantities of seaweed or debris, it may be useful to remove some of the chain on the guiding panel to minimize clogging. In addition, fishers may reduce towing speed for a few seconds at regular intervals to allow any weed and/or debris to drift out of the guiding panel and help keep the grid clear (see also Isaksen *et al.* 1992).

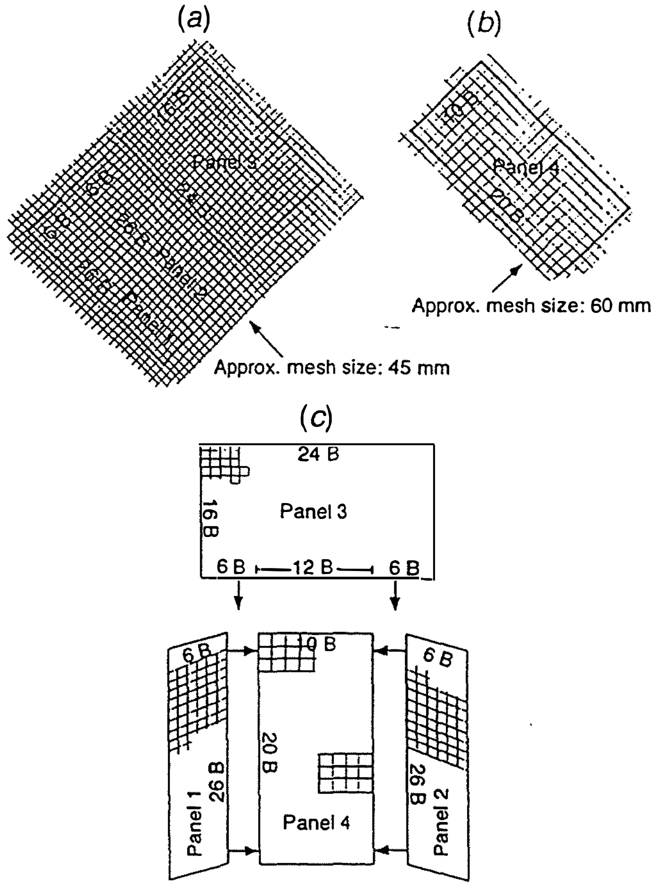

Fig. 5. Composite square-mesh panel: diagrammatic representation of netting required for *(a)* Panels 1, 2, 3 and *(b)* Panel 4; *(c)* assembly.

The composite square-mesh panel

The composite square-mesh panel (Fig. 1*b*) was developed for use in the NSW oceanic prawn-trawl fishery where it was found to exclude by-catch by up to 41% (including up to 70% of juveniles of commercially important species such as whiting, *Sillago* spp.) while maintaining catches of commercially important species and increasing catches of king prawns, ***Penaeus plebejus*** (by up to 14%) (see Broadhurst and Kennelly 1996*a*, 1997). This design functions by exploiting behavioural and physiological differences between prawns and fish. Some species of fish are herded together in the front section of the codend, upsetting the balance of the school and initiating an escape response towards the sides and top of the codend and out through the open square meshes (see also Robertson 1986, 1993). Contributing factors in the escape of these fish are differences in hydrodynamic pressure in front of the catch in the rear of the codend and a displacement of water forwards and out through the strategically positioned square meshes ahead of this section (Broadhurst and Kennelly 1996*a*). The response of prawns to this stimulus is minimal (Broadhurst and Kenelly 1996*a*) and, once in the trawl, they are unable to make active attempts at escape through the square-mesh panel.

Construction and installation

For use with most designs of penaeid prawn-trawls the composite square-mesh panel can be made as follows.

1. Cut Panels 1, 2 and 3 from netting with the same or similar sized mesh (and ply) as a conventional codend (i.e. 40 mm or greater) (Fig. 5*a*). This will make it easy to match and sew the composite square-mesh panel to the meshes in the top of the codend. .

2. Cut Panel 4 from netting with a larger mesh (e.g. 60 mm) made from 36-ply twine or greater (Fig. 5*b*). Although it is possible to use up to 90-mm mesh in the main escape panel, the results from experiments conducted in the NSW oceanic prawn-trawl fishery (Broadhurst and Kenelly 1996*a*, 1997) suggest that 60 mm is more suitable for fishers who seek to retain commercial-sized species such as red spot whiting, *Sillago flindersi* (>16 cm). The length and width of this panel will depend on the size of mesh used: to calculate the required length of Panel 4, measure the lengths of Panels 1 or 2 and then estimate how many bars of Panel 4 fit along this length; to estimate the width of Panel 4, determine the length of 12 bars of the smaller mesh (from Panels 1, 2 or 3) and the number of bars in Panel 4 that match this length.

made from lighter ply, it may be necessary to include an extra row of meshes across the top and bottom and along each of the sides. These can be 'picked up' (i.e. as a selvedge) when Panel 4 is sewn to Panels 1, 2 and 3.

3. After each of the square-mesh panels has been cut out, attach one side of each of Panels 1 and 2 to the sides of Panel 4. It is best to sew Panels 1 and 2 so that the square meshes pull in opposite directions (i.e. simply 'flip' either Panel 1 or 2 over before sewing; see Fig. 5*c*).

4. Evenly sew one side of Panel 3 to the anterior edges of Panels 1, 4 and 2 (Fig. 5*c*).

5. The composite square-mesh panel must be placed in the top of the codend as close as possible to the end. In codends made of two circumferences of mesh, it should be inserted in an area starting at least two meshes forward of the join between the two sections of the codend (i.e. in front of the join in the different circumferences of mesh). If the codend is composed entirely of a circumference of 100 meshes, it needs to be inserted approximately 25–33 meshes ahead of the end of the codend. The width and length of the piece of diamond-shaped mesh that needs to be cut from the top of the codend depends on the size of smaller mesh used to construct the composite square-mesh panel. To determine the number of diamond meshes that need to be cut in a transverse direction (i.e. width), measure the width of the composite square-mesh panel and then calculate the number of diamond meshes required to match this distance, assuming a fractional mesh opening of 0.25 × the stretched mesh length (see also Robertson 1986). For example, the width of the composite square-mesh panel shown in Fig. 5*c* is 540 mm (i.e. 24 bars × 22.5 mm) and the fractional opening of each 45-mm diamond mesh in the codend would be approximately 11.25 mm (i.e. 45 mm × 0.25). Therefore, to maintain consistent geometry around the codend, 48 of the diamond meshes (540 mm ÷ 11.25 mm) would need to be attached to the anterior and posterior ends of the composite square-mesh panel. However, because the composite square-mesh panel is attached to half a mesh either side of the opening in the top of the codend, only 47 diamond meshes need to be cut in the transversal direction (Fig. 6). To calculate the required number of diamond meshes that need to be cut in the normal direction (i.e. length), measure the length of the composite square-mesh panel and then calculate how many stretched diamond meshes equal this distance. If the smaller mesh used in the composite square-mesh panel is the same size as that used in the codend then two bars will measure the same distance as one mesh. For example, the composite square-mesh panel shown in Fig. 5 is 42 bars in length (45-mm mesh), requiring 21 diamond meshes (45-mm mesh) to be cut (e.g. Fig. 6).

6. The posterior end of the composite square-mesh panel are laced to the codend first, at a hanging rate of two transversal diamond-shaped meshes to one of the smaller square meshes. The remaining transversal diamond-shaped meshes (e.g. 23 T in Fig. 6) are spread evenly across the larger square meshes (60–90 mm). Both the sides and finally the anterior end are evenly laced to the codend. After installing the composite square-mesh panel, the 'lazyline' is attached to the codend in a manner ensuring that it remains clear of the square meshes during towing.

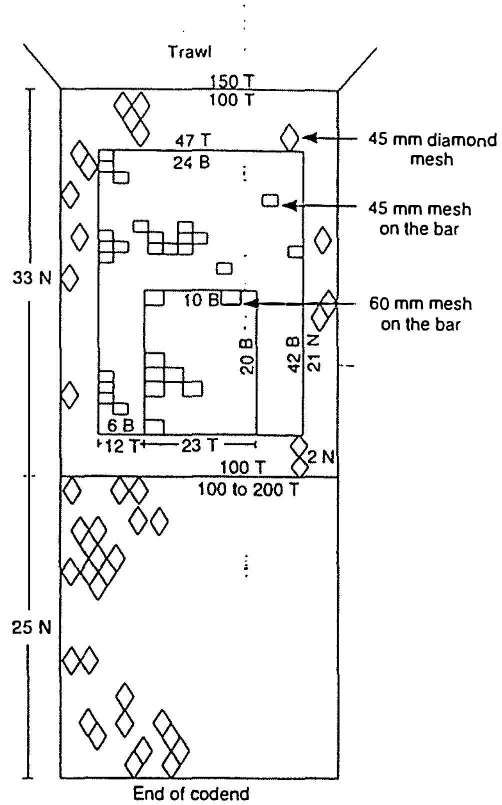

Fig. 6. Diagrammatic representation of assembled composite square-mesh panel.

The composite square-mesh panel has been designed so that the load is distributed anterior to, and lateral to, the larger mesh in the main escape panel (e.g. 60-mm mesh), thereby allowing it to remain open. It is important that this BRD be sewn in correctly to avoid changing the geometry of the codend (see also Robertson 1986, 1993). Because normal diamond mesh hung on the bar is used to construct the panel, the knots may slip. If this occurs, simply stretch the panel back into shape or, alternatively, construct the panel from heavier material (e.g. 3-mm braided twine).

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A Framework for Solving Bycatch Problems: Examples from New South Wales, Australia, the Eastern Pacific and the Northwest Atlantic

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Summary

A framework for solving bycatch problems is described that involves combining the respective expertises of scientists and fishermen. The first prerequisite for any attempt to ameliorate bycatch problems involves identifying and quantifying bycatches using large-scale observer programmes. These programmes involve scientists collecting information at sea from normal commercial fishing operations and so determine potential problems without relying on anecdotal information or data from research vessels. Once the species-specific distributions and abundances of bycatches are determined, modifications to fishing methods are tested in experiments using commercial fishing vessels. The fishermen's roles in this framework are: (i) to be seen as the driving force in addressing any conflicts that may come from their bycatches; (ii) to provide scientists with their unique practical knowledge of the relevant fishing technology; and (iii) to implement solutions into normal fishing operations efficiently and, in many cases, voluntarily. The scientists' role is to organize, analyse and disseminate the work, provide information on possible solutions through their access to the international literature and to ensure the scientific rigour of the experiments. Finally, both scientists and fishermen are responsible for communicating the solutions (and their adoption) to other fishermen, the public and special interest groups. The success of this approach is described using examples from the prawn trawl fisheries of New South Wales, Australia, the shrimp and fish trawl fisheries off the northeastern United States and the tuna purse-seine fisheries of the eastern Pacific.

Introduction

Earlier this decade, several authors correctly predicted that bycatch would become one of the most important fisheries issues of the 1990s (e.g. Klima 1993; Tillman 1993). Declining fish stocks in many of the world's fisheries, and widespread publicity over the incidental capture of charismatic species like dolphins and turtles, have led to commercial and recreational fishermen, conservationists, environmentalists, politicians, fisheries managers and scientists, all identifying bycatch as a key problem and calling for ways to reduce it (for recent reviews see Andrew and Pepperell 1992; Alverson *et al.* 1994; Kennelly 1995).

In recent years, scientists and fishermen in some countries have successfully solved certain bycatch problems in their respective fisheries. In considering the procedures followed in these cases, it is apparent that a relatively simple and logical framework was adopted that involves fishermen and scientists each applying their respective expertises to the problem. In short, this framework or protocol (see Fig. 1) involves identifying and quantifying the relevant problem (*via* observer programmes), solving the problem through modifications to commercial fishing gears and/or fishing practices, and then 'selling' these solutions throughout the particular fishery and finally to concerned interest groups.

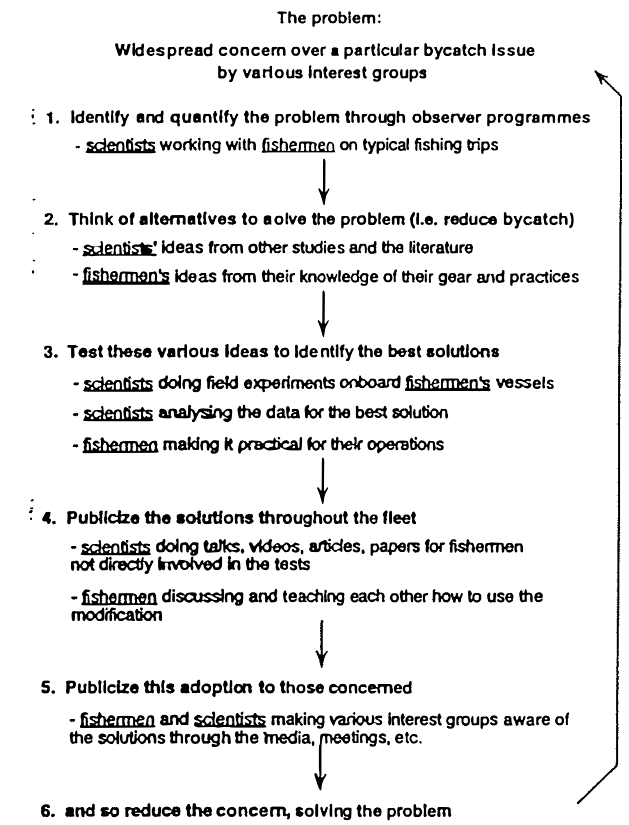

Fig. 1. The framework used to address bycatch problems.

The Framework to Address Bycatch Problems

Observer programmes

The first step in this framework is to identify and quantify the particular bycatch issue of concern by determining species-specific spatial and temporal variabilities in bycatches — so removing any reliance on qualitative or anecdotal information. Such data cannot be collected from information on commercial landings, nor can one rely on fishermen to provide accurate data on bycatches (it is often argued, in fact, that it is in fishermen's best interests *not* to provide such information). Further, one cannot rely on information gathered from research vessels because such data may not mimic that gathered with commercial fishing vessels, gears, operating procedures, targeting decisions, etc. It is well established that the best way to obtain bycatch information is for scientists (or scientific observers) to work alongside fishermen on their own vessels and to collect the data *in situ* by sorting, identifying, measuring, counting and weighing retained and discarded catches (see also Howell and Langan 1992; Saila 1983; Alverson *et al.* 1994; Kennelly 1995; Murawski *et al.* 1995). While such observer surveys assume that fishermen do not change their normal operations in the presence of observers, they nevertheless constitute the most accurate form of bycatch information that can be gathered.

It is during this stage of the framework that scientists, observers and fishermen usually forge working relationships that later prove vital in solving identified bycatch problems. It is worth noting that these relationships do not arise out of port meetings, conferences or workshops (these are all important and occur later in the framework), but are developed onboard many different vessels, at sea, in rivers, during long days and nights, working alongside each other sorting catches. Without several years of working alongside fishermen in this way, scientists usually are not in a position to solve bycatch problems for two reasons: (i) they lack the necessary data on bycatches which identify the particular issues that required solving; and (ii) they lack the respect from industry that is needed to work with them on solutions.

Once the observer information is available for a particular bycatch concern, it is necessary to consider whether the concern reflects a real or merely a perceived problem. If biological and stock parameters for the relevant bycatch species are available, can be incorporated with observer data, and show that the concern does not reflect a real problem to populations, then the best way to ameliorate the concern may involve education programmes aimed at particular interest groups. If, however, such analyses prove otherwise (that the concern reflects a real problem to populations) or, as is often the case, the relevant parameters are not available, then alternative ways to reduce bycatches may need to be considered.

Alternative solutions

Once the particular bycatch issue has been adequately identified and quantified, the scientists and fishermen are in a position to develop alternatives that aim to reduce the problem. Developing alternative modifications to fishing gears and practices to reduce unwanted bycatch is best done as a joint exercise: the scientists provide information gleaned from other studies, the scientific literature, conferences, etc. and from liaising directly with other scientists throughout the world; the local fishermen provide their unique practical knowledge of their fishing gears, vessels and grounds and how various modifications may be applied in their operations. In bringing together both types of expertise and experience, the scientists and fishermen eventually identify those modifications that warrant further consideration and field testing.

Testing the alternatives

Once various alternatives have been identified, the scientists and fishermen then test various selected modifications to gears and fishing practices *via* field trials onboard conventional commercial fishing vessels (usually chartered by the scientists). The scientists' role at this stage is to design rigorous field experiments and sampling protocols, and collect, analyse and write up the data as quality papers and reports that can pass critical peer review. The fishermen's role is to ensure that the proposed modifications and their fishing operations can be readily combined. Using commercial vessels to do this research (rather than research vessels) is vital because: (i) it supplies skippers and crews who possess local knowledge of the conventional methods used and local fishing grounds; (ii) it supplies control gears (e.g. conventional nets) and fishing practices against which the modifications can be tested; and

(iii) it ensures the interest and involvement of the rest of the fleet (i.e. those not chartered for the research) because the research is done with their colleagues, alongside them, in their grounds, using similar gears and vessels.

After preliminary trials, refinements to various modifications, and subsequent re-testing and refinement,scientists and fishermen eventually arrive at some solution(s) that they conclude works best in reducing the identified bycatch problem in their particular fishery.

Publicizing the results to other fishermen

While the graphs and analyses of the data from the field trials usually convince scientists and managers of the utility (or otherwise) of the modifications, the next step is to illustrate the success of these modifications to the rest of the fishery (i.e. including those fishermen who were not directly involved in the research). This is done by presenting photographs, videos, data and reports to as many fishermen in the fishery as possible, through meetings, dockside talks, workshops and encouraging the circulation of the information throughout the fishery. The fishermen involved in the trials also discuss the modifications with other fishermen and assist them in making and using the modifications. These new users then inform other users and eventually many members of the various fleets are using the modifications to reduce their unwanted bycatch — in some cases this has even occurred on a voluntary basis without any changes in regulations (see below).

Publicizing the solutions to the public

Unfortunately, reducing bycatch *via* the above protocol is insufficient by itself to resolve the concern from various interest groups over the particular bycatch issue (i.e. the initial problem). This final step can only be done by widespread publicity of the solution, its development, testing and acceptance by fishermen to those most concerned with the issue. This is usually achieved by the fishermen and scientists making presentations to committees that represent other commercial and recreational fisheries, conservationists, and environmentalists, and releasing photographs, videos, interviews, etc. to the print, radio and television media. Armed with such evidence (in addition to verifying the credibility of the work publishing the results in scientific journals), the scientists and fishermen involved are usually able to reduce the perceived problem and so reduce the concern identified as central to the initial problem.

EXAMPLES USING THE FRAMEWORK

Virtually all fisheries in the world have some bycatch associated with them (interestingly, one of the few fisheries that has negligible bycatch is whale harpooning where the only bycatch may include some barnacles). However, some types of fishing are recognized as having greater bycatch problems than others with two of the more infamous being: (i) demersal trawling for fish and prawns (or shrimp), which often results in the capture and discard of many juvenile fish that, when larger, would be targeted in other commerical and/or recreational fisheries; and (ii) purse seining around schools of dolphins for tuna, which has led to mortalities of large numbers of dolphins (for a recent review, see Alverson *et al.* 1994). Of the few cases throughout the world where successful solutions to bycatch problems have been developed, several have dealt with problems in these types of fisheries. The rest of this paper briefly summarizes a few examples of the way in which the above framework was (and is being) used to resolve various bycatch problems in these cases.

The prawn trawl fisheries of New South Wales, Australia

New South Wales, has experienced quite high-profile bycatch problems in its estuarine and oceanic prawn fisheries for many years (going as far back as the late 19th century — see Dannevig 1904; for review see Kennelly 1995). In the late 1980s these concerns reached a maximum and resulted in threats to close certain prawn fisheries to stop the bycatch of juvenile fish. At around this time it was discovered that, despite some anecdotal information, there were very few scientific data concerning this problem and so we began a large-scale observer programme was commenced in 1989 to identify and quantify the issue. This involved censussing catches on replicate, randomly selected vessels doing typical fishing trips in several estuaries and out from several oceanic ports throughout the State.

The data from the observer programme led to quite uncompromising information on the bycatches of juvenile fish by various prawn trawl fleets (for details see Kennelly 1993; Kennelly *et al.* 1993; Liggins and Kennelly 1996). For example, in the Clarence River estuarine fishery in the year 1991–92, it was estimated that in catching 270 t of prawns, this fishery discarded 123 t of bycatch, including ~0.8 million individuals of the recreationally and commercially important yellowfin bream. In the oceanic fishery offshore from this river in the same year, we estimated that in catching 288 t of prawns, 4022 t of bycatch was caught (including ~6 million red spot whiting — an important commercial species). Of this bycatch, an estimated 725 t was landed for sale as 'by-product' (including various species of slipper lobsters, squid, octopus and large fish) while the rest (some 3297 t) was discarded.

Information such as this was given to fishermen throughout NSW at various port meetings and as written reports to all fishermen involved. After some debate, these meetings eventually led to the scientists (and the fishermen) identifying the key bycatch problems in some detail (in terms of species-specific spatial and temporal patterns) and so made it possible to focus on possible solutions. In the example described above, the bycatch and discarding of large numbers of yellowfin bream were clearly seen as a problem for the Clarence River estuarine fishery. For the oceanic fishery, the bycatch of large numbers of small red spot whiting and other finfish was seen as a problem but (unlike the estuarine fishery) any solution in this fishery needed to take account of the fishermen's requirement to keep certain species of bycatch for sale as by-product.

Developing alternative modifications to trawl gears to reduce these unwanted bycatches was a joint exercise undertaken by scientists, fishermen and key net makers. The scientists supplied information from other studies, the scientific literature, international conferences and workshops, and from liaising directly with colleagues throughout the world (especially those

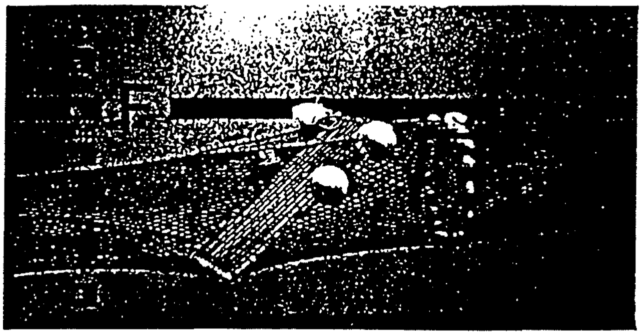

Fig. 2. The Nordmore grid design tested and now used in the Clarence River estuarine prawn trawl fishery

in Norway, Scotland and the United States). The local fishermen and netmakers from the Clarence River supplied their unique practical knowledge of their fishing gears, vessels and grounds and how various modifications could be applied in their operations. In this way, modifications were identified which warranted further consideration and field testing.

These discussions led to the testing of several kinds of Nordmore grids and square-mesh panels in these estuarine and oceanic fisheries *via* manipulative experiments onboard chartered commercial vessels set up to trawl in the conventional way. In general, these experiments took the form of paired comparisons of modified nets with conventional nets and were analysed using paired *t*-tests and analyses of variance (for details, see Broadhurst and Kennelly 1994; Broadhurst *et al.* 1996; and Broadhurst *et al.* in press).

Preliminary trials, refinements to various modifications, further testing, and refining, came up with two modifications for these fisheries that proved successful at reducing bycatch while maintaining and sometimes even enhancing catches of prawns. Because the targeted prawns (eastern school prawns) in the estuarine fishery were smaller than the bycatch to be excluded, a Nordmore grid was found to be most suitable for this fishery (Fig. 2). Figure 3 shows the striking difference in bycatches that came from using this grid in the fishery and the data shown in Figure 4 confirm these results with bycatches (including bream) being greatly reduced while prawn catches were maintained.

For the oceanic fishery, such grids were not appropriate because the targeted prawns (eastern king prawns) were quite large and the grids tended to exclude most of the by-product species which the fishermen wished to retain (slipper lobsters, octopus, squid, larger fish, etc.). For this fishery we developed a unique type of composite square-mesh panel anterior to the cod-end (see Fig. 5) — the theory being that small fish swam out of the cod-end with the water flowing through the panel while the less mobile prawns, slipper lobsters, squid and octopus would go to the back of the cod-end. The sizes of fish excluded in this way could be selected by adjusting the mesh size in the square-mesh panel. Figure 6 shows the effects of this panel on bycatches, and Figure 7 shows the data confirming these reductions in bycatches (including red spot whiting) whilst catches of prawns were maintained and even slightly enhanced [illegible] also had no effect on [illegible] Broadhurst *et al.* [illegible]

Fig. 3. Example of the catches from paired comparisons in the Clarence River estuarine prawn trawl fishery using a conventional cod-end (on the left) and one with a Nordmore grid (on the right)

Whilst the graphs and analyses of the data from the above trials convinced various anonymous referees of the usefulness of the modifications, it was the photographs (e.g. Figs 3 and 6), videos, and meetings with the chartered fishermen that

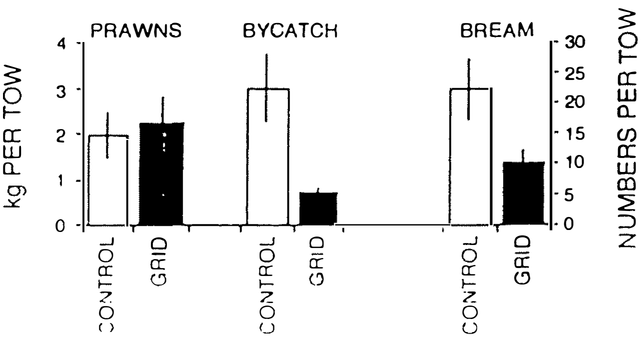

Fig. 4. Summaries of data (for weights of prawns and bycatch and numbers of bream) from comparisons of a cod-end with the Nordmore grid and a [illegible] cod-end [illegible] River estuarine prawn trawl fishery

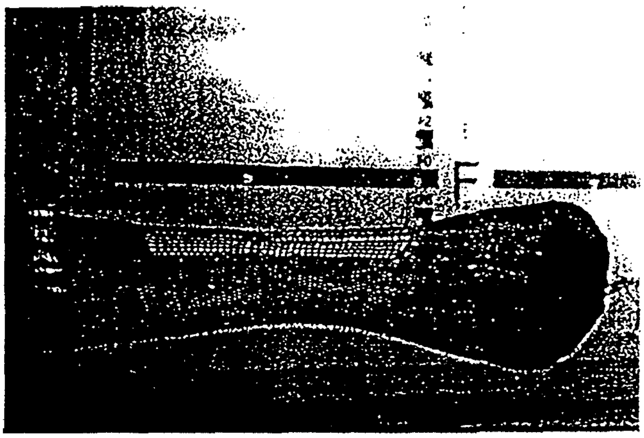

Fig. 5. The composite squaremesh panel modification tested and now used in NSW's oceanic prawn trawl fishery.

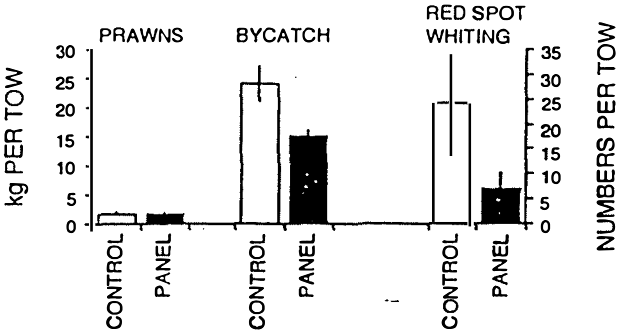

Fig. 7. Summaries of data (for weights of prawns and bycatch and numbers of red spot whiting) from comparisons of a cod-end with the composite square-mesh panel modification and a conventional cod-end in the Clarence River oceanic prawn trawl fishery.

illustrated the success of these modifications to fishermen who were not directly involved in the research. Distributed photographs and videos were distributed to fishermen in the relevant ports and the circulation of the information to other ports was encouraged. The fishermen involved in the trials discussed the modifications with other fishermen and assisted them in making and using the modifications. These new users then informed other users and before long, the majority of fishermen in the Clarence River estuarine and oceanic fisheries were using these gears and reducing their unwanted bycatches — all on a purely voluntary basis without any changes in regulations. News of these modifications has now spread to other ports and estuaries throughout NSW and southern Queensland and many fishermen in these other ports are now also using these gears voluntarily. We are currently in the process of ensuring that most of the fishermen in these other ports know about these modifications before their legislative adoption (which should result in complete compliance across these fisheries). Because of the widespread voluntary acceptance of the new gears, we believe that this last legislative step should be a relatively painless process.

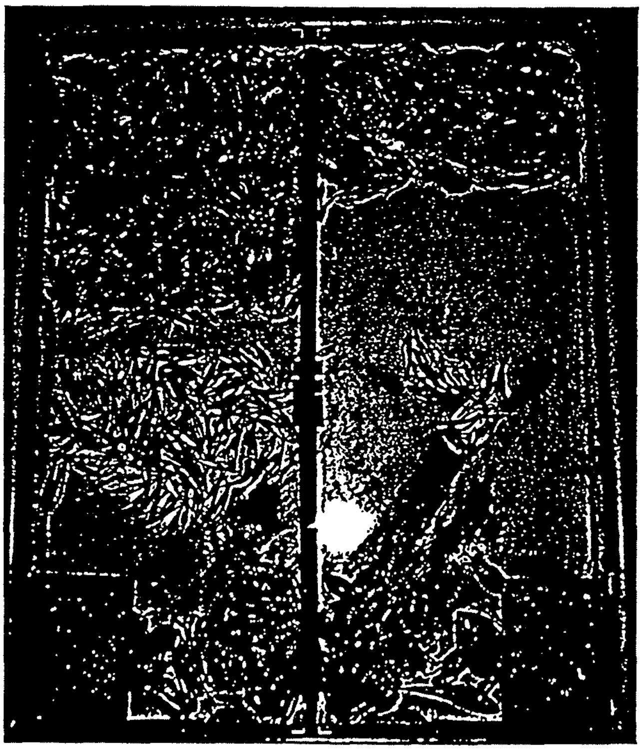

Fig. 6. Example of the catches from paired comparisons in the Clarence River oceanic prawn trawl fishery using a conventional cod-end (on the left) and one with the composite square-mesh panel modification (on the right)

The final stage in this work was to address the widespread concern from various interest groups over the issue. This has been done by widespread publicity of the solution, its development, testing and voluntary acceptance by fishermen to those most concerned with the issue. This is being achieved by the fishermen and scientists making presentations to committees (representing other commercial and recreational fisheries) and releasing photographs, videos, interviews etc. to the print, radio and television media. With such evidence (and the credibility achieved through the publication of the results in scientific journals), perceived problems concerning this issue in these fisheries were reduced.

Trawl fisheries in the northeastern United States

Like the prawn trawl fisheries in New South Wales and many other prawn and shrimp trawl fisheries throughout the world, the shrimp trawl fishery in the Gulf of Maine (in the northeast United States) has attracted substantial concern over its bycatch and discard of small fish (e.g. Howell and Langan 1992). Further, the solution of this issue in this region has followed a very similar path as that described above for NSW. Since 1988, the National Marine Fisheries Service has operated a large-scale observer programme in most of the fisheries in the region, supplying managers and scientists with their chief source of information on discards (e.g. see Murawski *et al.* 1995). The data from this programme identified and quantified the problems associated with bycatch from the shrimp fishery and, after a period of development by scientists and fishermen, a Nordmore grid system was introduced into the fishery to reduce unwanted bycatches (see Kenney *et al.* 1991, Richards and

Hendrickson 1995). While the introduction of this grid into this fishery was not done voluntarily but was mandated, there is now reasonable acceptance of the gear by shrimp trawlers and, because of the publicity surrounding the effectiveness of the gear and its acceptance, there has been a large decrease in concern over shrimp trawl bycatch in this region.

The groundfish trawl fisheries of the northeastern United States have also attracted their share of attention with regard to the discarding of other species and undersized individuals of target species. A summary of the observer data for these trawlers from 1990 to 1994 is seen in Table 1, which shows the average retained and discard rates (per trawl hour) of several important species. These summary figures highlight quite significant discarding rates for those species shown and more detailed analyses (Kennelly 1996) quantified the sorts of spatial and temporal patterns in discarding which, for several years, have caused significant conflicts with various user groups. For example, the discard of lobsters has caused conflict with lobster trappers, the discard of scup has caused problems with various recreational fishing groups and the discard of flatfish has caused problems with various commercial fisheries.

While the solutions to these problems for fish trawl gear may not be quite as simple as using Nordmore grids or square-mesh panels in shrimp trawls, recent developments in sorting devices for finfish and other species in fish trawl gear may provide some possible solutions. Modifications such as downward sorting grids and horizontal panels in nets have been shown to have great potential for reducing the bycatches of unwanted species and unwanted sizes of certain species in Norwegian groundfish trawls (see Isaksen 1993; Larsen and Isaksen 1993; Engas and West 1995) and scientists in the northeastern United States are currently working with local fishermen to test the effectiveness of some of these designs. Because of the existence of the large-scale observer programme, these scientists believe that the most difficult job in solving such bycatch problems is already in hand. That is: (i) they already have good observer data that identifies and quantifies the species-specific spatial and temporal scales of various problems, and (ii) they have established a working environment with fishermen that should enable such solutions to be tested, proven and eventually adopted.

Table 1. Summary of retained and discarded catches in the northeastern United States, 1990–1994: as estimated by the observer programme

	Retained (lbs/hour)	Discarded (lbs/hour)	% Discarded
Total catch (all species)	668.2	611.3	47.8
Lobster	1.4	1.9	57.9
Scup (porgy)	22.9	18.3	44.5
Butterfish	55.9	26.4	32.1
Red Hake	12.4	34.8	73.7
Silver Hake	182.2	33.3	15.4
Yellowtail flounder	9.9	3.9	28.3
Winter flounder	10.9	2.7	20.0
American plaice	4.8	1.5	23.4
Windowpane flounder	4.3	5.0	53.8

Tuna purse-seine fisheries of the eastern Pacific

In recent years, Martin Hall (Head of the Tuna-Dolphin Program at the Inter-American Tropical Tuna Commission) has described in several papers the success of the tuna purse-seine fisheries of the eastern Pacific in reducing the mortality of incidentally-caught dolphins (Hall 1994; Hall in press *a* and *b*). This particular bycatch issue has been one of the most infamous in the world since the 1960s with very dramatic outcries from Greenpeace and other environmental and conservation organizations. Fortunately, this fishery has had very high observer coverage, with most trips by most vessels covered, so information on discarding is quite thorough and has led to an excellent understanding of the dolphin issue and ways to solve it.

The most common way purse seiners fish in this region is to encircle groups of dolphins to catch the tuna that they swim with. In the early years of the fishery, the incidental mortality of dolphins using this method was quite high (an average of ~ 350000 dolphins/year during the 1960s) which is believed to have caused significant declines in populations of dolphins in the region. In the 1960s and 1970s, fishermen developed ways to reduce these mortalities and dolphin mortalities dropped to 20000 to 40000/year in the early 1980s. After this time, however, new entrants into the fishery and more targeting on dolphins led to increases in dolphin mortalities (133000 in 1986).

However, since that time, dolphin mortalities have been reduced by about 97% (to 3300 in 1995) through the development of a series of modifications to the purse seines used, the release practices of the encircled dolphins, and the education and training of skippers and crews in the techniques and special skills required. These modifications were developed over time by fishermen and scientists and involved a variety of operational and gear modifications, e.g. different mesh sizes were incorporated into certain sections of the purse seines used, a different method was developed for tying the cork line, a manoeuvre termed 'backdown' after dolphins were encircled was developed (Medina 1994), speedboats and dolphin rescue boats were incorporated into operations, and key places containing populations of dolphins particularly prone to discard mortality were avoided. Next, once such modifications were developed, they were shown to participating fishermen in a large-scale education programme that included the training of skippers and crews in the new techniques. Many of the programmes developed by the staff of the IAATC's Tuna–Dolphin programme have been implemented by an international agreement called the Panama Declaration which led to widespread adoption of the various modifications by fishermen. The success involved in reducing this bycatch problem is now being publicized to the various conservation and environmental organizations to the point where the widespread concern over this issue is gradually declining. Currently, Greenpeace, World Wildlife Fund, Environmental Defense Fund and the Center for Marine Conservation are supporting these programmes. In summary, the success of the work done in this fishery by the scientists and fishermen involved has shown that it was possible to save the dolphins without closing a major fishery.

Conclusions

A common point made whenever bycatch issues are discussed is that, while most fisheries have bycatch and many have particular bycatch problems, there are no easy 'quick fixes' to these problems (see also Alverson *et al.* 1994; Pitcher and Chuenpagdee 1994). The number and variety of bycatch problems in the world's fisheries are at least as numerous and complex as the fisheries themselves and no simple solution will work for all problems. (The marked success of the Nordmore Grid in many of the world's prawn and shrimp fisheries suggests that this device may be as close as one gets to a generic solution to prawn and shrimp trawl bycatch problems — although it too has its limitations if the targeted prawns are larger than or of a similar size to the unwanted bycatch). Despite the need for fishery-specific solutions to bycatch issues, however, this paper has demonstrated that in several very disparate cases where bycatch issues have been resolved, the fishermen and scientists involved have tended to adhere to a certain common protocol. These successes would suggest that subsequent attempts to ameliorate bycatch problems in other fisheries should at least consider such a framework as a useful way to begin.

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オーストラリア，ニューサウスウェールズ州エビトロールにおける混獲対策：乗船観察調査と選択漁具研究

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Solving By-catch Issues in The Prawn Trawl Fisheries of New South Wales, Australia: Observer Programmes and Selective Gear Research

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エビトロールにおける混獲は，ニューサウスウェールズ州（以下 NSW 州）の河口域や沖合域でも 19 世紀末から長年にわたって問題とされてきた。この地域では，キング・プラウン *Penaeus plebejus* やイースタン・スクール・プラウン *Metapenaeus macleay* を主に漁獲するエビトロールによって多くの小型魚が混獲，投棄されていた。1980 年代の終わりにはエビトロールに対して混獲や投棄を止めるように，他漁業などから圧力がかかるに至った。NSW 水産研究所では，その実態を明らかにするための混獲量を定量化する乗船観察調査を大規模に行い，さらに漁具改良による問題解決をはかった。

乗船観察調査　科学的な知識を持つ乗船観察員が，トロール漁船の操業中に船上で魚種別の混獲量を場所や時間毎に記録した。1989–92 年に NSW 州の数ヶ所の河口域と沖合域で標本船を無作為に選び，この調査を行った。

調査結果から幼稚魚の混獲実態が明らかになった。クラーレンス川河口では，1991–92 年にエビ 270 トンの漁獲に対して遊魚対象魚イエローフィン・ブリーム 80 万尾を含む 123 トンが混獲された。また沖合域では 1990–92 年にエビ 1,579 トンの漁獲に対して 16,435 トンの混獲があった。このうち，2,952 トンが副産物（セミエビ，イカ，タコ，大型魚を含む）として水揚げされた一方で，レッド・スポット・ホワイティング 130 万尾を含む約 13,458 トンが投棄された。

この結果は，州から漁業者に対して報告書配布と報告会を通じて伝えられた。これによって混獲の問題点が明らかになり，実行可能な解決策が議論された。上述した例では，イエローフィン・ブリームの混獲は，クラーレンス川河口域における問題として認識された。また，沖合域の漁業では，小型のレッド・スポット・ホワイティングやその他の魚の混獲が認められたが，河口域とは異なり，ここでは副産物として販売できる混獲魚を漁業者が確保できるように考慮するべきであった。

選択漁具研究と漁業者への普及　世界中から収集した選択漁具に関する資料をもとに，エビトロール漁業者と話し合い，角目網パネルとノルウェー式グリッドをこの海域で試験することを決めた。この試験を用船で行った理由は次のことによる。一つは用船した漁船の船長や乗組員はエビ漁場と通常の操業方法に関する知識を持っている。次に，漁業者が通常用いる漁具を改良型漁具の対照実験にできる。さらに，用船しなかった漁船もすぐ近くで操業することでなんらかの関わりを持ちうる。

漁具の改良と試験が繰り返され，いくつかの改良型漁具に到達した。河口域のエビトロールでは，漁獲対象のエビ（イースタン・スクール・プラウン）は保護対象魚よりも小さいので，改良型ノルウェー式グリッドが適切であった。沖合域の漁業でのグリッド使用は，河口域よりも大型のエビや確保するべき副産物がグリッドによって網から逃げて適当でない。この漁業では，コッドエンド前部に数種の目合の角目網パネルを組み合わせて取り付けた，いわゆる複合型角目網パネルが適切であった。この網パネルでは，あまり泳がないエビや副産物種はコッドエンドに入るのに対して，小型魚は網パネルから泳ぎ出る。この魚の大きさは角目網パネルの目合で調整できる。この試験結果（図 1）より改良漁具はエビを確保しながら不要な魚の混獲を減らすことができる。

この結果は，写真やビデオと報告会を通じて漁業者に伝えられた。そして，これら地域のエビトロール漁業者の大多数が自主的に改良漁具を導入することで，規制措置なしに混獲物を減らすことができた。

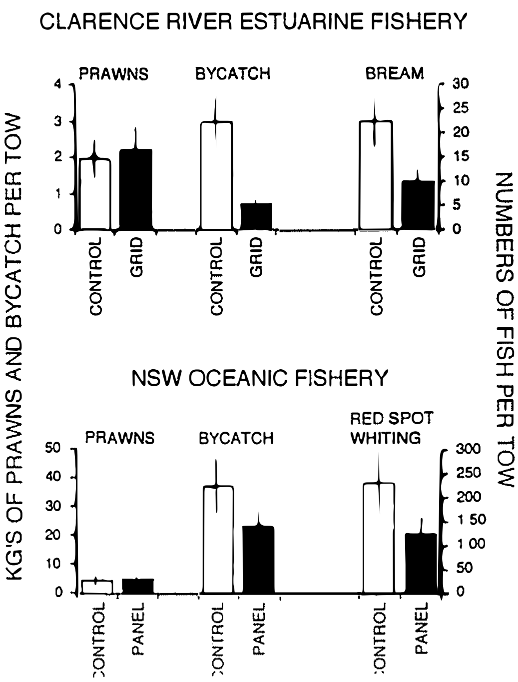

図 1　改良型と通常漁具における一曳網当たりの漁獲尾数の比較（上，改良型グリッド；下，複合型角目網）。

Flow-related effects due to codend mesh circumference and simulated weight of catch in prawn-trawl codends: potential for increasing the escape of unwanted fish through square-mesh panels.

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Flow-related effects due to codend mesh circumference and simulated weight of catch in prawn-trawl codends: potential for increasing the escape of unwanted fish through square-mesh panels

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Abstract

Two experiments were done in a flume tank to quantify the effects of codend mesh circumference on water flow. The mesh circumference of the posterior section of prawn-trawl codends (with and without by-catch reducing square-mesh panels) were assessed with three weights of catch (30 kg, 50 kg and 70 kg). Compared to a codend made with a circumference of 100 meshes throughout its entire length, a codend with an anterior section of 100 meshes and a posterior section 200 meshes in circumference significantly increased the displacement of water forwards (up to 1120 mm from the end of the codend). This result varied with the weight of catch in the codend. The second experiment involved placing composite panels of square-shaped mesh (by-catch reducing devices) into the tops of the anterior sections of two codends with the same configurations as those above (termed the 100 and 200 panel codends). There was a displacement of water forwards immediately under the square-mesh panel in the 200 panel codend (by up to 2200 mm from the end of the codend). The results are discussed in terms of: (i) the probable effects that codend mesh circumference and water displacement in codends have on fish behavior, and (ii) implications for the future development of by-catch reducing devices like square-mesh panels in prawn-trawls.

Key words: By-catch reduction; Square-mesh panels; Hydrodynamics; Prawn-trawls; Codend mesh circumference.

Oceanic prawn-trawling occurs from 9 major ports in New South Wales (NSW) Australia and has a total value of approximately A$17 million per annum. The principal target species is the eastern king prawn (*Penaeus plebejus*) although a significant proportion of the total value is derived from the sale of legally retained by-catch comprising individuals of several species of fish, crustaceans and cephalopods (see Kennelly, 1995). In addition to this landed catch, however, significant numbers of non-target organisms of no commercial value are also captured and discarded, including juvenile fish of species which, when larger, are targeted in other commercial and recreational fisheries (Kennelly, 1995).

Concerns over the incidental capture and mortality of large numbers of juveniles have led to the development of various by-catch reducing devices (BRDs), designed to minimize undesirable by-catch while maintaining catches of prawns and other commercially valuable individuals (Broadhurst et al., 1996; Broadhurst and Kennelly, 1996; 1997). In particular, a new design comprised of composite panels of square-shaped mesh (referred to as the composite square-mesh panel) was shown to increase catches of prawns (by up to 14%) (Broadhurst and Kennelly, 1997) while significantly reducing up to 40% of total unwanted by-catch and up to 70% of the numbers of small individuals of commercially important species such as whiting (*Sillago* spp.) (Broadhurst and Kennelly, 1996).

The results from these experiments were attributed primarily to differences in the behavior of fish and prawns in the trawl. Fish were believed to have been herded close together in the anterior section of the codend, upsetting the normal balance of the school and initiating an escape response towards the sides and top of the net and out through the open square-shaped meshes (Broadhurst and Kennelly, 1996). A contributing factor towards this escape was thought to be the effects on water flow due to the circumference of meshes in the posterior section of the codend. In an experiment to test this hypothesis, Broadhurst and Kennelly (1996) showed that a conventional codend made from an anterior section of 100 meshes circumference and a posterior section 200 meshes in circumference (a common commercial configuration) was less selective (i.e. retained more by-catch) than a conventional codend with a 100 mesh circumference throughout its entire length (see also Robertson and Stewart, 1988; Armstrong et al., 1990; Reeves et al., 1992; Galbraith et al., 1994). However, a comparison of codends with the same netting configurations as above but containing composite square-mesh panels located in their anterior sections showed that the effects on selectivity due to increased circumference in the posterior section were negated by a significant increase in the escape of small fish (e.g. red spot whiting, *Sillago flindersi*) through the square-meshes.

These results led to the hypothesis that increased twine area and smaller mesh openings in codends with posterior sections of 200 meshes circumference, increased the displacement of water forwards and out through the meshes in the anterior section (see also Watson, 1989). In turn, this water movement may have: (i) physically directed small fish out through the strategically-positioned composite square-mesh panel; (ii) assisted them to maintain station in front of the catch in the codend, increasing their likelihood of randomly encountering square-meshes; and/or (iii) stimulated their lateral line receptors and so their overall escape response. The reaction of prawns to this stimuli was thought to be minimal, given their inability to sustain escape responses in trawls (see Lochhead, 1961; Newland and Chapman, 1989).

While the results from the paper discussed above led to several hypotheses about changes in water flow and fish behavior due to changes in codend geometry, we lacked the quantitative information on flow rates necessary to support or refute them. Such information is important for developing new designs of codends and understanding where to position square-mesh panels and other BRDs. Our goals in the present study were to quantify the effects on water flow at various positions in codends and under square-mesh panels in two flume tank experiments. We simulated commercial conditions in the flume tank by using different weights of catch in various codend designs tested.

Materials and methods

Two experiments were done in May 1996 at the Australian Maritime College using the Faculty of Fisheries and Marine Environment's flume tank. This facility consists of a recirculating flow tank of fresh water, measuring 17.2 m long, 5 m wide and 2.5 m deep and comprises three levels: (i) an upper level where nets, etc are placed into the tank, (ii) an observation level, with a continuous perspex viewing-window and (iii) a water return channel. The two lower levels feature a series of delivery bends and screens that maintain constant water velocity throughout the depth of the tank without any swirls or vortices. Several electric motors, hydraulic pumps and impellor shafts provide water flow of up to 1.5 m s^{-1}.

An electromagnetic current meter was attached to the base of a stainless steel stanchion (Fig. 1A) and linked to a computer via a coaxial cable. The stanchion was attached to a moveable carriage positioned on rails over the upper level of the flume tank. This assembly enabled the current meter to be repeatedly located at several predetermined positions within the tank.

A full-scale Florida flyer prawn-trawl (mesh size 40 mm of 18 ply twine) with a headline length of 5.4 m, was rigged to two fixed stanchions, located on the sides of the forward section of the flume tank. The trawl was rigged with a zipper (No. 10 nylon open-ended auto-lock plastic slides) to facilitate changing the codends. The codends used in the experiments were of normal commercial size and materials, measuring 58 meshes long (2.3 m) and constructed from 40 mm mesh netting and 60 ply UV-stabilized high-density polyethylene twine. These codends were comprised of two sections: the anterior section was 33 meshes long and attached to a zipper; the posterior section was 25 meshes long (for details see Fig. 1, B and C - see also Broadhurst and Kennelly, 1996).

Experiment 1

Two codend designs were compared. The codends (termed the 100 and 200 commercial codends) were made entirely of diamond-shaped meshes and were comprised of anterior sections with a circumference of 100 meshes, attached to posterior sections with circumferences of 100 and 200 meshes respectively (Fig. 1, B and C). Three incisions of the same size as the width of the current meter's stanchion (three meshes in length), were made in the tops of each codend at distances of 2200 mm, 1120 mm and 560 mm forward from the end of the codends to facilitate placement of the current meter inside the codends (Fig. 1B).

Experiment 2

The two codends compared in this experiment were similar to the 100 and 200 commercial codends described above but included composite square-mesh panels made of 60 mm and 40 mm netting (36 ply and 48 ply UV-stabilized high-density polyethylene twine, respectively) cut on the bar and inserted into the tops of the anterior sections (termed the 100 panel and 200 panel codends) (for details see Fig. 1C and Broadhurst and Kennelly, 1996). Because the current meter (and not its stanchion) was inserted only 5 cm into the tops of the codends (Fig. 1C), it was not necessary to cut the meshes of these codends. Instead, four positions were labeled with a permanent marker at 2200 mm, 1720 mm, 1490 mm and 1130 mm forward from the end of the codends (Fig. 1C).

Experimental procedure

Thirty five rubber balloons were each filled with 2 l of water, providing a total mass in air of 70 kg. These balloons were used to simulate masses of catch in the codends. In each experiment, the two codends were tested alternately. The particular codend to be examined was attached to the trawl and loaded initially with 15 balloons (i.e. 30 kg). The hydraulic pumps in the flume tank were activated and adjusted to produce a flow of 1.2 m s^{-1} (the standard towing speed during commercial operations). After a stabilizing period of 10 minutes, the stanchion containing the current meter was alternately lowered into each of the predetermined positions in the codends (three in experiment 1 and four in experiment 2). After a further stabilizing period of 1 minute at each position, the current meter was switched on and left for a period of one minute during which the flow of water immediately anterior to the current meter was recorded at one second intervals and the data sent to the computer. The mean flow rate from each minute of recording was calculated from these data and used in subsequent analyses. After each reading, the current meter was moved to the next position and the procedure repeated. After six replicate readings were collected for each position, the flow of water in the flume tank was reduced to approx. 0.5 m s^{-1} and additional balloons were added to the trawl to simulate an increase in the volume of catch. The above procedure was then repeated to obtain data on the flow of water at each position with 50 kg (25 balloons) and 70 kg (35 balloons) in each codend.

Data analysis

Data collected in each experiment were examined using Cochran's test for homogeneity of variances and transformed if necessary. Data from experiment 1 were analyzed in a three-factor fully orthogonal, balanced analysis of variance. The factors were codends, positions and weights. Data from experiment 2 were analyzed at each position in two-factor fully orthogonal, balanced analyses of variance (Underwood, 1981). Significant differences detected in these analyses were investigated by Student-Newman-Keuls (SNK) multiple comparisons of means.

Results

Experiment 1

The analysis of variance showed that there were significant differences in flow rates between the type of codend, position of the current meter and weight in the codend, and significant interactions among codend-type, positions and weights (Table 1). SNK tests showed that mean water flow was greatest at position no. 2 (1.162 m s^{-1}) in the 100 commercial codend with a catch of 30 kg and lowest at position no. 3 (0.709 m s^{-1}) in the 200 commercial codend with 70 kg (Fig. 2). SNK tests also showed that, compared to the 100 commercial codend, there was a significant reduction in mean water flow in the 200 commercial codend with 30 kg at position no. 2 (mean difference of 0.071 m s^{-1}) and across all three weights (30 kg, 50 kg and 70 kg) at position no. 3 (mean differences of 0.203 m s^{-1}, 0.176 m s^{-1} and 0.184 m s^{-1}, respectively) (Fig. 2; Table 1). While SNK tests did not detect differences in mean water flow between codends with 50 kg and 70 kg at position no. 2 nor across all weights at position no. 1, these combinations of weight and position showed similar trends as those described above - i.e. a mean reduction in water flow by the 200 commercial codend (Fig. 2).

Experiment 2

There were significant differences in the mean water flow between the type of codend at position nos. 2, 3 and 4 and between weights at position nos. 2 and 3 (Table 2). There was a significant interaction between the type of codend and weight at position no. 1. SNK tests detected differences in the mean flow rates between the 100 and 200 panel codends at position nos. 1, 3 and 4 (Fig. 3). Compared to the 100 panel codend, there was significantly less water flow in the 200 panel codend with a catch of 70 kg at position no. 1 (0.115 m s^{-1} difference between means) and at position no. 3 with 50 kg (difference of 0.102 m s^{-1}) (Fig. 3, A and C; Table 2). Conversely, at position no. 4, SNK tests detected an increase in the mean water flow in the 200 panel codend with a catch of 30 kg compared to the 100 panel codend (difference of 0.067 m s^{-1}) (Fig. 3D). There was also a similar, although not significant result for 50 kg at this position. There were no other significant differences although, at position nos. 2 and 3 there were similar trends across all weights (i.e. a reduction in water flow in the 200 panel codend) (Fig. 3B and C).

Discussion

This study showed that the weight of catches and the configuration of the posterior section in codends can have significant effects on the displacement of water in the anterior section of codends. In interpreting these results, it is important to note that under the simulated conditions in the present study, water was forced through a stationary trawl (at 1.2 m s^{-1}). Any localized displacements of water forwards in the codends examined in this study, therefore, can be expressed as a reduction in the flow entering the trawl and calculated by subtraction from 1.2 m s^{-1}.

The flow of water at all positions in the 4 codends tested was less than 1.2 m s^{-1}, indicating that there was displacement of water anterior to the catch. However, the degree of this anterior water displacement varied significantly between the codends tested in each experiment (Figs. 2 and 3). For example, in experiment 1, the 200 commercial codend showed a significant increase (compared to the 100 commercial codend) in the displacement of water forwards at position no. 3 across all weights of catch (difference in mean flow of up to 0.203 m s^{-1} - Fig. 2 and Table 1). These differences in flow may be attributed primarily to the distribution of the balloons used to simulate catch in the two codends and consequent changes in codend geometry. In the 200 commercial codend, the balloons were observed to spread out evenly in the posterior section, providing a greater surface area of catch incidental to the flow than in the 100 commercial codend. This effect, combined with the increase in the area of twine in the 200 commercial codend probably caused an increase in the displacement of water forwards in this codend.

The above effects in the 200 commercial codend were also detected at position no. 2 with 30 kg of balloons and, although the ANOVA failed to detect significant differences for the other weights at this position, the trends in the results were similar (i.e. a reduction in flow in the 200 commercial codend compared to the 100 commercial codend - Fig. 2 and Table 1). At position no. 1, for all weights, the force of the displaced water in front of the 200 commercial codend had dissipated to the extent where there were no significant differences between the two codends (Fig. 2 and Table 1). It can be assumed, therefore, that the major influence of increased codend circumference on water displacement in the middle of the 200 commercial codend probably occurred up to some point between position nos. 2 and 3 (560 mm to 1120 mm from the end of the codend), relative to the weight of catch.

In experiment 2, the effects of increased codend circumference on water displacement under the square-mesh panel were detectable at a greater distance from the end of the codend than those described above. Compared to the 100 panel codend, there were significant reductions in flow (corresponding to an increased displacement of water forwards) in the 200 panel codend at position nos. 1 and 3 (2200 mm and 1490 mm from end of the codend) with a weight of catch of 70 kg and 50 kg, respectively (mean differences in flow of 0.115 m s^{-1} and 0.102 m s^{-1}, respectively) (Fig. 3A and C; Table 2). Although not significant, there were similar trends at position no. 2 for each weight and at position no. 3 for 30 kg and 70 kg (Fig. 3B and C; Table 2). In contrast, there was a significant increase in the flow of water at position no. 4 in the 200 panel codend with 30 kg and a similar result (though not statistically significant) for 50 kg (Fig. 3D; Table 2). This anomaly may be explained by the fact that the balloons in the 200 panel codend (like those in the 200 commercial codend) were orientated evenly across the surface area of the posterior section, increasing its diameter and decreasing the angle of incidence of its netting as it leads into the anterior section of the codend at position no. 4. Although the current meter was located immediately under the composite square-mesh panel, at this position it was effectively aligned slightly above the anterior section of the codend and may have been influenced by the current outside the trawl, negating some of the flow-related effects of codend mesh circumference.

With the exception of this latter result, the measured reductions in flow at most positions in the 200 codends (corresponding to increases in water displacement forwards) support the hypothesis that an increase in the circumference of meshes in the codend contributes towards the escape of small fish (between 5 and 20 cm) through the composite square-mesh panel (see Broadhurst and Kennelly, 1996; 1997). The size of these fish suggests that they are using anaerobic muscle power to maintain position in the moving trawl (1.2 m s^{-1}) and are fatigued when they enter the codend (see Beamish, 1978; Wardle, 1989). A relatively small increase in the displacement of water forwards (e.g. 0.203 m s^{-1} at position no. 3 in the 200 commercial codend or 0.1 m s^{-1} at position no. 3 in the 200 panel codend) may be sufficient to (i) assist small fish to swim forwards and out through the square-meshes in the panel and/or (ii) enable them to reduce their tail-beat frequencies and maintain their position in the codend for a longer period, increasing their chances of random escape through the panel and/or (iii) stimulate their lateral line receptors and so their overall escape.

Without direct observations of fish swimming in the codend, it is difficult to determine their specific behavior during escape. Whatever their actual escape-mechanism, however, the results obtained in this study provide important information for the subsequent design and location of BRDs like the composite square-mesh panel. It is apparent that to maximize the effects of anteriorly displaced water in the posterior section of codends, the composite square-mesh panel should be located as close as possible to the end of the codend, but sufficiently forward of the anticipated build-up of catch to prevent prawns from accumulating past the square-meshes and escaping through them. A solution to this problem would be to increase the codend mesh circumference in the posterior panel (i.e. the 200 panel codend), causing the catch to spread laterally in the back of the codend, rather than accumulate forwards. Whilst such a modification would also increase surface area, the displacement of water forwards and probably enhance fish escape through the square-mesh panel, it would also reduce mesh openings and the selectivity of the codend itself (Broadhurst and Kennelly, 1996).

An alternative modification which may increase displacement of water forwards (other than increasing codend circumference and catch) is to move the composite square-mesh panel forward in the codend and create areas of "artificial catch" using semi-porous panels (e.g. fine mesh). These could be positioned on the bottom of the codend, posterior to the panel and at an angle to the direction of tow (e.g. see Fig. 4). Such modifications should produce similar flow-related effects as those observed in this study: i.e. displacing water anteriorly, directing fish towards the panel. Future research into the refinement of square-mesh panels and other BRDs in prawn-trawls that exploit the behavioral differences of fish in trawls, may benefit from these or similar modifications.

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Captions to figures

Fig. 1. Diagrammatic representation of (A) the current meter and its stanchion, (B) 100 and 200 commercial codends and the 3 positions of water flow readings and (C) 100 and 200 panel codends and the 4 positions of water flow readings.

Fig. 2. Differences in mean flow rates ± SE between the 100 and 200 commercial codends tested in experiment 1 (< and > indicate direction of differences in SNK tests).

Fig. 3. Differences in mean flow rates ± SE between the 100 and 200 panel codends tested in experiment 2 for each position of the current meter and for different weights (< and > indicate direction of differences in SNK tests of means).

Fig. 4. Diagrammatic representation of proposed modification to codends containing the composite square-mesh panel.

TABLE 1. - Summaries of F ratios from the analysis of variance to determine effects on water flow due to different codends (i.e. 100 and 200 commercial codends), position of current meter and weight in the codend. The sqrt(x) transform was used to stabilize variances. In all tables *P =<0.05; **P = <0.01.

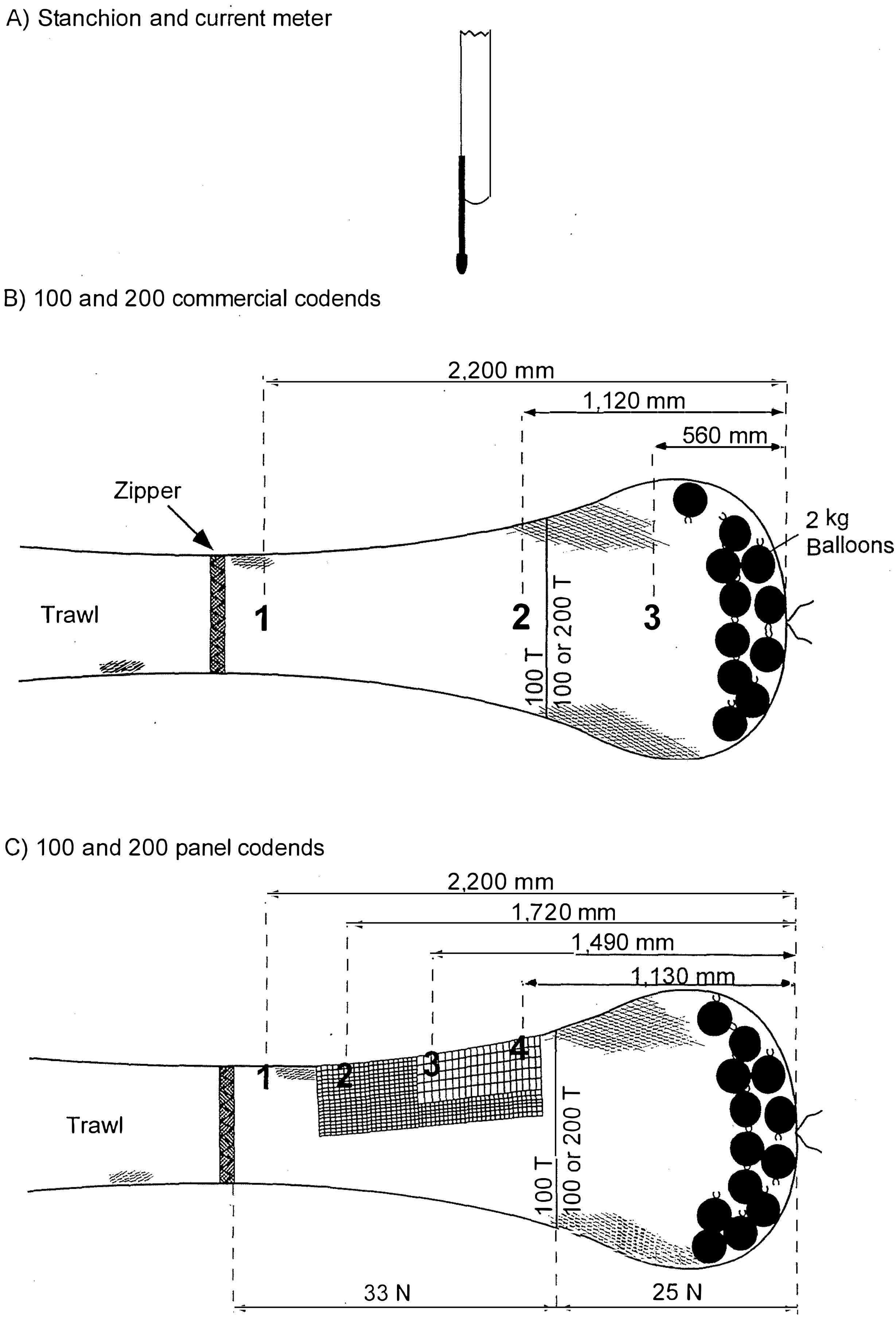
Treatment	d.f.	Water flow (m s^{-1})
Codends (C)	1	162.52**
Position (P)	2	388.16**
Weight (W)	2	62.42**
C x P	2	35.01**
C x W	2	8.04**
P x W	4	12.39**
C x P x W	4	0.81
Residual	90	

TABLE 2. - Summaries of F ratios from analyses of variance to determine effects on water flow at different positions due to different codends (i.e. 100 panel vs 200 panel), and weights. The transforms used to stabilize variances (if required) are also listed.

Treatment	d.f.	Position no. 1	Position no. 2	Position no. 3	Position no. 4
				sqrt(x)	
Codend (C)	1	2.21	5.88*	5.16*	7.92**
Weight (W)	2	2.29	3.95*	8.56**	1.34
C x W	2	7.81**	0.87	0.74	2.77
Residual	30				

TABLE 3 - Summaries of histopathology done on 2 randomly selected fish from each treatment and control tank in group 2, experiment 2. Fish that died during the experiment are in bold type and fish that survived the experiment are in plain type; (T) treatment tank; (C), control tank; Lengths in centimetres; Scale-loss in percent; (+++, ++, +, 0) severe, high, moderate and none.

Tank no.	Fish no.	Fish length	Day of mortality	Total scale-loss	Diffuse hyperplasia	Focal hyperplasia	Fusion of filaments	Copepods	Cryptocaryon	Blood vessel lesions	Epitheliocystis
T1	**1**	**10.5**	**29**	**10.1**	**++**	**++**	**+**	**++**	**+**	**+**	**0**
T1	**2**	**14**	**30**	**1.5**	**+**	**+++**	**+**	**+**	**++**	**+**	**+**
T2	**1**	**10.5**	**28**	**3**	**+++**	**++**	**+**	**+**	**+**	**+**	**+**
T2	**2**	**10**	**29**	**0**	**++**	**++**	**++**	**+**	**++**	**++**	**+**
T3	**1**	**10**	**39**	**0**	**++**	**++**	**++**	**+**	**0**	**0**	**+**
T3	**2**	**10**	**40**	**0**	**++**	**+++**	**++**	**+**	**++**	**+**	**+**
T4	**1**	**11.5**	**40**	**2**	**++**	**++**	**++**	**+**	**+**	**+**	**+**
T4	**2**	**9.5**	**40**	**0**	**++**	**0**	**0**	**0**	**++**	**0**	**0**
T5	1	10.5	40	0	+	+++	+++	+	+	+	+
T5	2	10	40	0	++	++	+	+	+	+	+
C1	**1**	**10.5**	**37**	**2**	**++**	**++**	**0**	**+**	**+**	**+**	**+**
C1	**2**	**10**	**38**	**0**	**+++**	**++**	**++**	**+**	**+**	**0**	**0**
C2	1	10	40	0	+++	+	+	0	+++	0	0
C2	2	9	40	0	+	++	+	+	+	+	+
C3	1	12	40	0	++	++	++	+	+	+	+
C3	2	8.5	40	0	+	++	++	+	+	0	0
C4	1	8	40	0	+	++	0	0	+	0	+
C4	2	11	40	0	+	+++	++	++	++	0	+
C5	1	9	40	0	+	++	+	++	++	0	+
C5	2	9.5	40	0	+	++	+	+	+	0	0



A) Stanchion and current meter
B) 100 and 200 commercial codends
2,200 mm
1,120 mm
560 mm
Zipper
2 kg Balloons
Trawl
1
2
3
100 T
100 or 200 T
C) 100 and 200 panel codends
2,200 mm
1,720 mm
1,490 mm
1,130 mm
Trawl
1
2
3
4
100 T
100 or 200 T
33 N
25 N

FIG 1

NORMAL COMMERCIAL CODENDS

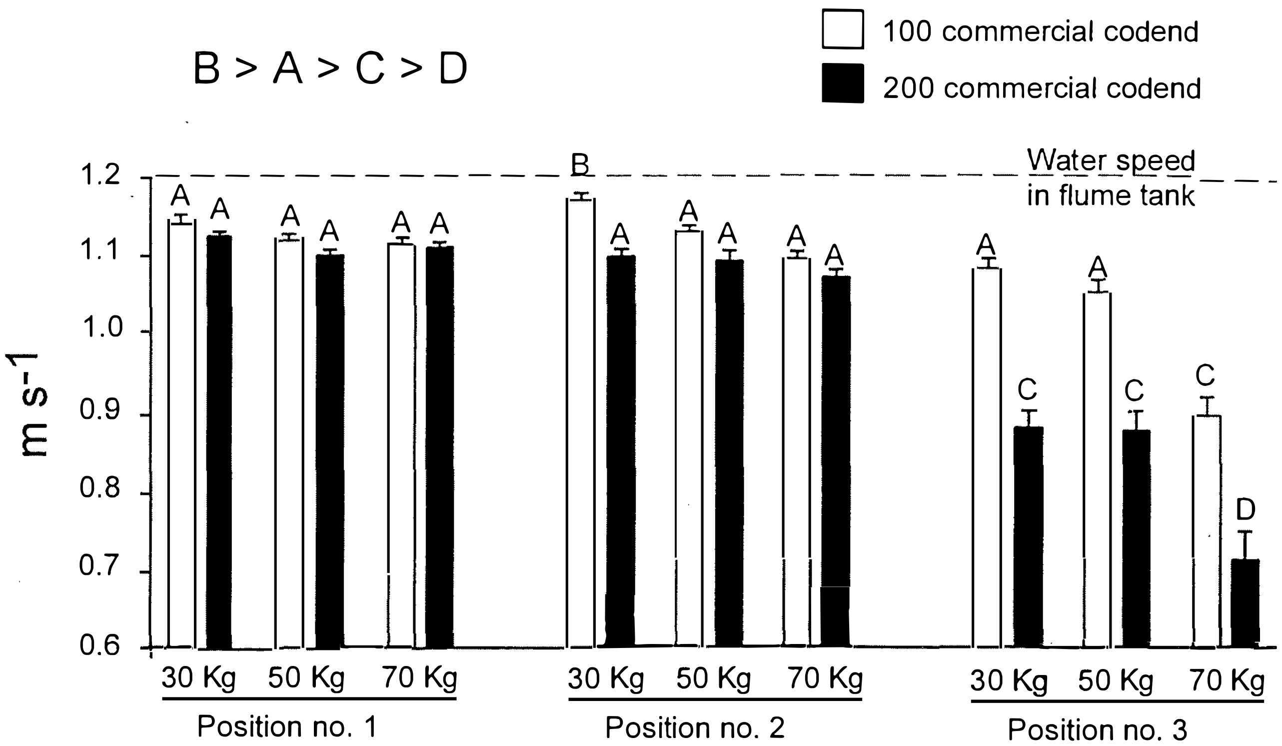
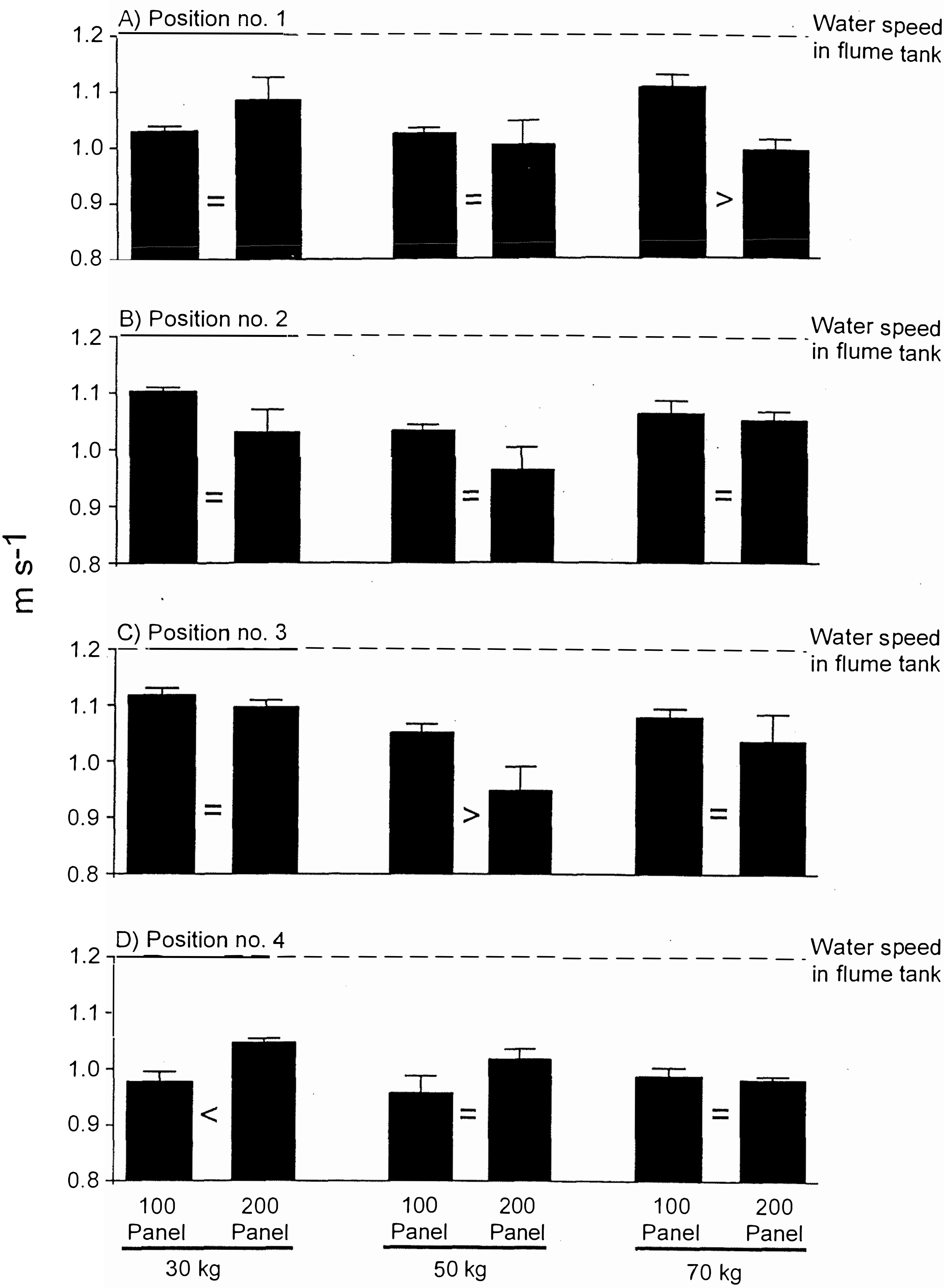


FIG 2



A) Position no. 1
B) Position no. 2
C) Position no. 3
D) Position no. 4
Water speed in flume tank
m s-1
1.2
1.1
1.0
0.9
0.8
=
>
<
100 Panel
200 Panel
30 kg
50 kg
70 kg

FIG 3

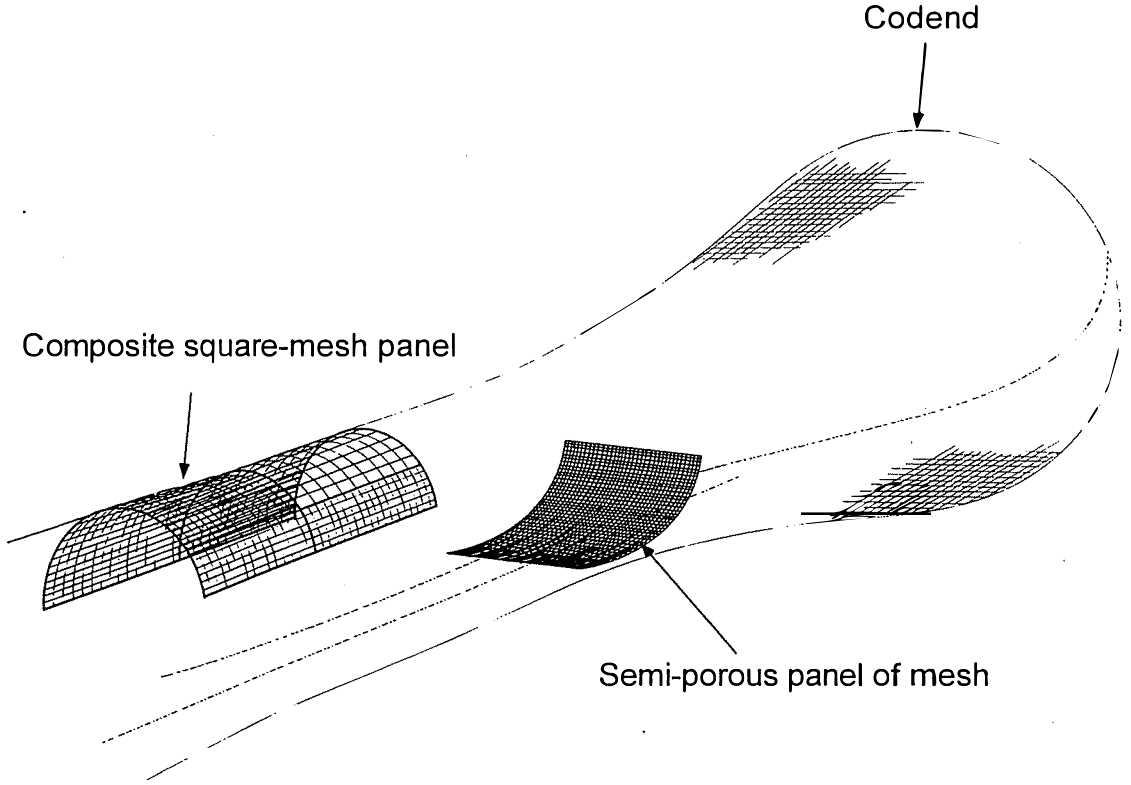

Codend
Composite square-mesh panel
Semi-porous panel of mesh

FIG 4

Scale-loss and survival of juvenile yellowfin bream, *Acanthopagrus australis*, after simulated escape from a Nordmore Grid guiding panel and release from capture by hook and line.

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SCALE-LOSS AND SURVIVAL OF JUVENILE YELLOWFIN BREAM, *ACANTHOPAGRUS AUSTRALIS*, AFTER SIMULATED ESCAPE FROM A NORDMØRE-GRID GUIDING PANEL AND RELEASE FROM CAPTURE BY HOOK AND LINE

Matt K. Broadhurst, David T. Barker and Steven J. Kennelly

ABSTRACT

Two laboratory experiments were done to assess the scale-loss and survival of juvenile yellowfin bream, *Acanthopagrus australis* after (i) simulated escape through the guiding panel of a Nordmore-grid and (ii) release after capture by hook and line. In both experiments the total scale-loss on treatment fish was quite low (< 3%). In experiment 1, yellowfin bream that were fatigued to exhaustion and forced to pass through a guiding panel showed significantly more scale-loss at, and posterior to, their area of maximum height than fish that were fatigued but did not pass through the guiding panel (60.5% to 80% difference in means). In experiment 2, fish that were hooked and then released lost significantly more scales across their entire body than did control fish (79% to 87% difference in means). There were negligible mortalities over the duration of experiment 1 (30 days). In experiment 2, all fish in four treatment tanks (40 fish) and one control tank (10 fish) died due to hyperplasia and fusion of gill filaments caused by copepods and protozoan parasites. The results are discussed in terms of the likely stresses incurred by fish due to the fishing gears tested in each experiment and the aquarium systems used.

Yellowfin bream, *Acanthopagrus australis*, is a common marine fish that typically inhabits estuarine and coastal waters throughout much of New South Wales (NSW), Australia (Pollock, 1982). Their accessibility in estuaries and aggressive behaviour makes them a popular target species for recreational hook and line fishers. They are also taken commercially as a target species by gill netters, fish trappers and beach seiners and as an incidental catch (or 'by-catch' - sensu Saila, 1982) from prawn-trawlers working in estuaries (Liggins and Kennelly, 1996).

Minimum-size regulations prohibit recreational and commercial fishers from retaining yellowfin bream less than 25 cm (total length). However, because none of the fishing gears that catch this species only select legally sized fish, some component of the total catch is usually discarded. While discarding of undersized individuals occurs to some extent throughout all fisheries, in recent years a particular concern to a broad section of the community in NSW has been the incidental capture and discard of juvenile yellowfin bream by estuarine prawn-trawlers and the negative impacts that this may have on stocks (Kennelly, 1995; Liggins and Kennelly, 1996).

These concerns led to a three-year observer based study that quantified the distributions and abundances of key by-catch species throughout the prawn-trawl fisheries of NSW (Kennelly, 1993). The information collected revealed relatively large by-catches of juvenile yellowfin bream in the Clarence River (mean catches of up to 829 000 fish per year) and Lake Wooloweyah (up to 348 000 fish per year) (Liggins and Kennelly, 1996). To minimise these by-catches, several designs of by-catch reducing devices (BRDs) were developed and tested in these fisheries (Broadhurst and Kennelly, 1996; Broadhurst et al., 1996). Of these designs, a rigid separator panel termed the Nordmøre-grid (see also Isaksen et al., 1992) was shown to be effective in reducing the mean weight of total by-catch (by between 77% and 90%) and the numbers of juvenile yellowfin bream (< 25 cm) (by up to 67%) with no significant reduction in catches of the targeted prawns. This research led to the voluntary adoption of the Nordmøre-grid by many fishers throughout NSW estuaries, particularly in the Clarence River and Lake Wooloweyah.

Whilst the application of BRDs like the Nordmøre-grid in prawn-trawls has partly addressed the issue of the capture and discarding of juveniles of yellowfin bream in the Clarence River and Lake Wooloweyah, there is little information on the levels of discarding associated with other large-scale fisheries and, in particular, those involving recreational hook and line. Recreational harvests from NSW have been documented in several roving creel surveys (see Henry 1984; Henry et al., 1987; West and Gordon, 1994; Steffe, et al., 1997). Whilst these studies have provided evidence to suggest that recreational anglers catch and illegally retain significant numbers of juveniles of species such as yellowfin bream (e.g. Henry, 1984; Henry et al., 1987; West and

Gordon, 1994), there are virtually no data available on the levels of discarding of undersize fish by these anglers. In addition, the lack of any formal selectivity studies on recreational fishing gears makes it difficult to estimate the probability of catching undersized fish and therefore precludes the use of management options for recreational fisheries involving gear restrictions. Minimum size-restrictions are used extensively to manage these fisheries but for these to be effective in preserving stocks, a large proportion of undersized fish that are caught and discarded should survive.

In order to determine the longer-term benefits that management options such as minimum size-limits in recreational fisheries and BRDs in prawn-trawls will have on stocks of species such as yellowfin bream, it is important to provide an assessment of the damage that fish sustain during contact with particular fishing gears and the proportion that survive after escape (for reviews see Muoneke and Childress, 1994; Chopin and Arimoto, 1995). Our specific goals in this study were to quantify the scale-loss and survival of juvenile yellowfin bream after (i) simulated escape from the Nordmøre-grid and (ii) release from capture by hook and line.

METHODS

Two experiments were done at NSW Fisheries Research Institute's aquarium facilities between June 1996 and January 1997 using two 4000 l fibreglass holding tanks and 22 smaller 200 l fibreglass tanks. All tanks were supplied with seawater (at an ambient temperature - range of 17 - 21^0 C) at a rate of 1.8 l min^{-1}, aerated using air-stone diffusers and equipped with outflow pipes (termed 'stand-pipes'), designed to maintain constant water levels. The small tanks were distributed on opposite sides of an enclosed room and had their stand-pipes located in their centres (see Fig. 1(A) and Broadhurst et al., 1997).

Collection of fish for experiments. - Juvenile yellowfin bream (< 20 cm) were caught at two locations using two different fishing gears: approximately 650 fish were caught in the Hawkesbury River (33° 34'S, 151° 15'E) from a depth of 2 - 3 m using a prawn-trawl (mesh size 40 mm) and approximately 410 fish were caught in a small tributary leading into Botany Bay (33° 59'S, 151° 08'E) from a depth of 1 m using a seine net (mesh size 15 mm). After capture at both locations, fish were carefully removed from the codend or net, placed in holding tanks (400 l - stocking density of < 5 kg fish per cubic metre) at ambient temperature (17 - 21^0 C) and supplied with pure oxygen. These fish were transported to the aquarium facility and transferred (using buckets) to the 4000 l holding tanks (fish captured by each method were kept in separate 4000 l tanks). To reduce the possibility of infection arising from initial capture, a solution of 100 mg/l of Oxytetracycline was added to each holding tank and water flow was stopped for 6 hours.

Depending on the level of post-capture mortality (see results), fish were allowed to acclimatise in the large holding tanks for a period of between 21 days (fish captured by seine net) and 100 days (fish captured by prawn-trawl) during which time they were fed a diet of chopped pilchards (at a rate of 1% biomass per day). Any mortalities were removed immediately and recorded. Any faeces and uneaten food that settled in the tanks were removed daily by siphon.

Experiment 1: Effects on fatigued fish due to passing through the guiding panel of the Nordmøre-grid. - In previous field studies that used underwater video to record the behaviour of fish passing through Nordmøre-grids, it was observed that most yellowfin bream avoided contact with the aluminium grid after passing through the guiding panel (Broadhurst and Kennelly, pers obs). It was apparent that most of the damage to these fish (if any) occurred as they were herded together in the narrow taper of the guiding panel and passed under the chain at the posterior end of the panel. To examine the extent of physical damage and mortality associated with the escape of fish from the Nordmøre-grid, we therefore simulated the escape of yellowfin bream through the guiding panel.

A 12 V submersible water pump assembly was modified so that it could replace the stand-pipes in each of the 200 l tanks (Fig. 1B). Included in this assembly was a cylinder of PVC (250 mm dia x 600 mm long - Fig. 1B) designed to (i) prevent fish from physical contact with the pump and (ii) concentrate fish into a smaller volume of water in each tank (see also Broadhurst et al., 1997). Two identical aluminium frames were constructed so that they could be inserted between the outside wall of the PVC cylinder and the inside wall of the 200 l tanks (Fig. 2A, B). The first frame was rigged with a panel of mesh constructed similar to the posterior quarter of the guiding panel in the Nordmøre-grid (Fig. 2A). As is the case for the Nordmøre-grid used in NSW estuaries, four links of 6 mm diameter chain were attached to the top of the posterior end of the guiding panel. The second frame was fitted with a panel of fine-meshed polyethylene (Fig. 2B). These two panels could be placed along side each other, and rotated freely throughout the entire volume of the tank (Fig. 2C).

After 21 days, the fish that were captured by seine net in the 4000 l holding tank were anaesthetised using benzocaine (ethyl p-aminobenzoate, 50-75 mg/l in sea water - see also Quartararo and Bell, 1992). Two hundred and twenty fish (ranging in size from 7- 14.5 cm) were selected at random, individually checked for any signs of scale-damage (any damaged fish were left in the holding tank), removed (using buckets filled with water) and then placed in groups of 10 into the 22 smaller tanks. These fish were fed and monitored (using the methods outlined above for the 4000 l holding tanks) and left to acclimatise for a further 10 days. At the end of this second acclimatising period, 18 of the tanks were randomly designated as either treatments or controls (9 of each). To maintain constant stocking densities throughout the experiment, fish in the remaining 4 tanks (stock tanks) were used to replace any mortalities in the treatment and control tanks.

On day 1 of experiment 1, the stand-pipes were removed in each treatment and control tank and replaced with the water pump assembly (Fig. 1B). The pump was activated, producing a circulating water flow of between 0.7 and 0.8 knots within each of the tanks for 15 minutes (flow was measured using an electromagnetic current meter). During this period, the fish were observed to orientate towards the direction of flow and maintain station until exhausted (approximately 10 minutes for most fish). This treatment simulated the exhaustion incurred by fish as they are herded in the trawl.

At the end of 15 minutes, the two aluminium frames were inserted into the treatment tanks and rotated in opposite directions, so that fish were herded together and forced to swim through the guiding panel (Fig. 2C). Fish did not come into any contact with the frame containing the fine-meshed polyethylene. In each of the control tanks, this frame was used to herd fish once around the tank. These fish were herded like the treatment fish but did not come into contact with any mesh.

The treatment and control tanks were divided at random into two groups: group 1 contained 4 treatment and 4 control tanks and was used to assess scale-loss. Group 2 contained 5 treatment and 5 control tanks and was used to assess total mortalities.

Experiment 2: Effects on fish due to capture by hook and line. - At the end of experiment 1, 80 fish from the 4000 l holding tanks containing fish that were captured by prawn-trawl and the fish from the control and stock tanks used in experiment 1 were anaesthetised using benzocaine, checked for any signs of scale-damage and transferred to the other 4000 l holding tank (containing fish that were originally captured by seine net). These fish were left to acclimatise for 10 days. At the end of this period all fish (ranging in size from 7- 14.5 cm) were anaesthetised and 130 fish were randomly selected, individually checked for any signs of scale-damage, removed and placed in groups of 10 into 13 randomly selected smaller tanks. Nine of these tanks were designated as control tanks and 4 were stock tanks.

Using Mustang No. 12 long-shanked hooks attached to light monofilament line (8 kg) and baited with pieces of pilchards and prawns, 90 fish were hooked in the mouth and 'caught' from the 4000 l holding tank. After capture, fish were held firmly with one hand for between 10 and 40 seconds while the hook was removed. These fish were then placed in buckets in groups of 10 and transferred to the remaining 9 smaller (treatment) tanks.

As was the case in experiment 1, the treatment and control tanks were divided at random into two groups: group 1 contained 4 treatment and 4 control tanks and was used to assess scale-loss. Group 2 contained 5 treatment and 5 control tanks and was used to assess total mortalities.

Analysis of scale-loss. - Every second day after the start of each experiment, all fish in each tank from group 1 were anaesthetised (as described above). Two fish were then randomly selected from each tank and carefully removed (using gloves and firmly holding each fish by the head and tail) and killed in a solution of benzocaine (100 mg/l in sea water). These fish were measured (to the nearest 0.5 cm) and placed ventrally on clear plastic sheets inscribed with silhouettes of fish (the same length and width as each of the samples) divided into five zones per flank (Fig. 3). Using the method described in Main and Sangster (1988), both sides of each fish were visually subdivided and the percentage scale-loss determined (to the nearest 5%) for each of the five zones on both flanks. The means of these 10 values provided estimates of the scale-loss from all zones combined for each fish (see also Main and Sangster, 1988). Each fish was then weighed. In experiment 2, fish were also examined for damage directly caused by hooks and the location (i.e. mandible, premaxillary, maxillary, ethmoid or throat) of lesions (if any) were recorded.

Data for percentage scale-loss per zone and combinations of various zones were analysed using Cochran's test for homogeneity of variances, and then analysed in the appropriate three-factor analyses of variance (Underwood, 1981). Treatment of fish and observation days were considered fixed factors in these analyses, tanks were random and nested in treatments and the two random fish per tank per observation-day were the replicates.

Analysis of total mortality. - Fish in group 2 in both experiments were monitored daily for any mortalities (30 days in experiment 1 and 40 days in experiment 2). All dead individuals were immediately removed from their tanks and replaced with the same number of live fish (which had a small section of caudal fin removed for identification) from a stocking tank. Dead fish were analysed for scale-loss as per the methodology described above. Because a significant number of fish died in experiment 2 we histopathologically examined these fish to determine cause of death. Initially, all fish that died in the treatment and control tanks in group 2 of this experiment were examined for scale-loss and individually placed in plastic jars containing 10% formalin in sea water. Two randomly selected fish from each treatment and control tank were then sent to the Regional Veterinary Laboratory in Menagle, NSW for histopathological analyses. At the end of experiment 2, to examine the histopathology of surviving fish, 2 randomly selected fish from each treatment and control tank in group 2 that had no mortalities were killed and sent for histopathological analyses.

RESULTS

Collection of fish for experiments. - Four hundred and fifty eight yellowfin bream, representing approximately 70% of the 650 fish captured by prawn-trawl, died during the first 20 days in the 4000 l holding tank. Most of these dead fish showed evidence of severe physical trauma (i.e. scale -loss) that was probably inflicted during capture (e.g. due to weight of catch and contact with the meshes in the codend). There were no mortalities of fish captured by the seine-net in the 4000 l holding tank nor during the acclimatising period in the 200 l tanks.

Experiment 1: Scale-loss from fatigued fish due to passing through the guiding panel of the Nordmøre-grid. - There were no mortalities of fish in group 1 (the scale-loss group) that were attributable to passing through the guiding panel, however, three fish managed to jump out of a treatment tank. Scale-loss from fish that passed through the guiding panel was < 2 % for all zones combined. However, compared to fish from the control tanks, treatment fish showed significantly more scale-loss for zones no. 1 and 3 and all zones combined (difference in means of 80%, 60% and 60.5%, respectively) (Fig. 4A, C, E, Table 1). Although non-significant there were similar trends as above for zones no. 2 and 4 (difference in means of 28% and 56.5%, respectively) (Fig. 4B, D, Table 1). There was a significant interaction between days and treatment of fish for zone no. 4 (Table 1).

Experiment 1: Total mortality of fatigued fish due to passing through the guiding panel of the Nordmøre-grid. - One fish in a treatment tank died on the first day of the experiment after passing through the guiding funnel, resulting in a total survival rate of 98% of fish from group 2. There were no mortalities of fish in the control tanks.

Experiment 2: Scale-loss from fish due to capture by hook and line. - There were no mortalities of fish in group 1 that were attributable to being hooked, although one fish managed to jump out of a control tank. The majority of fish were hooked in their mouth-parts (Fig. 5) and sustained minor damage. Scale-loss was quite low (< 3%) across all zones combined. However, there was significantly more scale-loss from each zone on fish in treatment tanks than fish in control tanks (difference between means of 79% to 87%) (Fig. 6, Table 2). There were significant interactions between days and tanks for zone no 4 and between days and treatment of fish for all zones combined (Table 2).

Experiment 2: Total mortality of fish due to capture by hook and line. - All fish in four of the treatment tanks (40 fish) and one of the control tanks (10 fish) died after the 27th day. Results from histopathology showed no differences between fish that died during the experiment and those that were killed at the end (Table 3). All fish from all tanks had severe gill pathology (e.g. hyperplasia, fusion of filaments and blood vessel lesions) associated with the presence of copepods, *Alella macrotrachelus,* and protozoan parasites (e.g. cryptocaryon) (Table 3).

DISCUSSION

The results from this study have shown some of the effects that the escape of yellowfin bream from two different fishing gears can have on their scales, mortality and susceptibility to infection. By conducting two separate experiments incorporating different methods and treatments we have also provided a preliminary assessment of the benefits of BRDs in prawn-trawls and minimum-size restrictions on this species for recreational hook and line fisheries.

Compared to control fish in experiment 1, fish that passed through the guiding panel of the Nordmøre-grid showed significant differences in the mean percentage scale-loss for zones no. 1 and 3 and all zones combined (differences of 80%, 60% and 65%, respectively) and, although not significant, there were also differences in mean scale-loss for zones no. 2 and 4 (Fig. 4). An explanation for the significant differences in scale-loss at zones no. 1 and 3 (at, and posterior to, the area of maximum height) may be attributed to the behaviour of fish during escape. It was observed that many fish struggled after making contact with the closed end of the guiding panel and then twisted laterally as they passed through. These fish probably lost scales at their maximum height during initial contact and then along their posterior flanks at zone no. 3 as they attempted to assume their normal swimming action. Although the movement of these fish through the guiding panel resulted in the loss of significantly more scales than control fish, the total amount of scale-loss was quite low (i.e. a total combined mean scale-loss of < 2% from treatment fish - Fig. 4E) and apparently not sufficient to contribute to any significant mortalities over the duration of the experiment (30 days).

In experiment 2, treatment fish sustained some damage as a result of contact with the hook, although in the majority of cases this was confined to minor lesions of mouth-parts (Fig. 5). Treatment fish did sustain significantly more scale-damage across all zones than control fish (differences between means of 79% to 87% - Fig. 6), however, like the similar sized yellowfin bream that passed through the guiding panel in experiment 1, the overall average percentage scale-loss was quite low (< 3% - Fig. 6E). Despite these results, all fish in four of the treatment tanks and one of the control tanks from group 2 died.

While mortalities of fish in the treatment tanks occurred earlier and in greater numbers, the histopathological results showed that nearly all fish from all tanks (i.e. control and treatment tanks) in experiment 2 had severe hyperplasia and fusion of gill filaments caused by large quantities of copepods and protozoan parasites (Table 3). Both these agents are found in wild populations of fish and are considered capable of causing mortalities (Needham and Wootten, 1978). Given their levels of their infestation in all fish in experiment 2 (due to the confined conditions of the tanks) the remaining four control tanks and one treatment tank probably would have eventually incurred mortalities had the experiment continued beyond 40 days.

Because there were 100% mortalities in each of 5 tanks, fish within each tank could not be considered to be independant of each other (i.e. when one fish died due to parasites, all fish in that tank subsequently died). This reduced levels of replication from the numbers of fish (n = 50) to the numbers of tanks (n = 5), precluding the use of conventional statistical analyses to determine the significance of the results. Nevertheless, the mortality of most of the treatment fish after almost 4 weeks compared to only 10 control fish suggests that the stress associated with being hooked and then released may have hastened these fishes' susceptibility to infection (see also Maule et al., 1987; Pankhurst and Sharples, 1992; Muoneke and Childress, 1994). However, given that all fish died in one control tank and there were high levels of pathogens in fish from all tanks, it is likely that the effects of confinement and/or the experimental methodology also contributed to stress levels and overall mortality (see also Gustaveston et al., 1991; Pankhurst and Sharples, 1992; Chopin and Arimoto, 1995).

In previous studies, analyses of physiological changes to the blood chemistry of fish have been used to determine the amount of stress caused by different treatments (Mazeaud et al., 1977; Soivio et al., 1977; Gustaveson et al., 1991; Ferguson and Tufts, 1992; Pankhurst and Sharples, 1992). In particular, elevations in concentrations of plasma cortisol (e.g. Pankhurst and Sharples, 1992), blood lactate and hyperglycaemia (e.g. Gustaveson et al., 1991) have been shown to contribute to longer-terms effects such as a lowered immune response to pathogens (Maule et al., 1987). In the present study, we quantified physical damage incurred during escape or release (e.g. scale-loss) and, although this may provide evidence of immediate post-escape/release damage, it does not quantify more subtle stress-related effects on physiology. For example, whilst the physical damage to fish in both experiments was comparatively low (< 3% scale-loss) other stresses may have caused various physiological changes. In experiment 1, fish were allowed to acclimatise in the 200 l tanks for 10 days at constant stocking densities. They were then fatigued in a current and treatment fish were quickly passed through the guiding panel of the Nordmøre-grid and 'released' while control fish were simply herded around the tank. Except for physical contact with the mesh of the guiding panel by treatment fish (resulting in minimal scale-loss), after the initial acclimatisation period the stresses incurred were mainly limited to those associated with fatigue. In experiment 2, however, all fish were anaesthetised, removed from the 4000 l tank (treatment fish were hooked, control fish were transferred by buckets) and placed in the smaller 200 l tanks on day one of the experiment - allowing no period of acclimation in the smaller tanks and different stocking densities. In addition, treatment fish were probably fatigued after struggling against the hook during initial capture and handling in air. Any reductions in the oxygen content in their blood during this exposure to air may have contributed significantly to their overall stress (see Ferguson and Tuffs, 1992). The cumulative effect of these various stresses in experiment 2 may have lowered the immune response of all fish, but mainly treatment fish, increasing their susceptibility to the pathogens.

This study has partly addressed the value of BRDs in prawn-trawls, and minimum size-limits for recreational hook and line fisheries as appropriate tools for conserving juveniles of yellowfin bream. For example, it is evident from the results that the physical damage to fish sustained during capture by hook and line and escape from the Nordmøre-grid were similar (< 3% scale-loss) and small compared to their respective controls. However, while the effects on fish escaping from the guiding panel appeared to have been limited to physical damage, there was some evidence to suggest that fish which were caught by hook and line and then discarded suffered more longer-term effects that may have contributed to their post-capture mortality. It is unknown, however, to what extent these sorts of effects, observed in the confined conditions of the aquaria, reflect what actually occurs to fish in wild populations. For example, fish in wild populations may not be exposed to the same levels of copepods and protozoan parasites as those in the aquaria. This uncertainty, combined with a lack of information on the influences of other fishery-specific effects (e.g. contact with the trawl, secondary re-capture and escape, different levels of fatigue, effects of different hook types and sizes, locations of hooking, duration of time spent on the line, exposure time in air, etc.) makes it difficult to extrapolate the results from this study to the respective fisheries in NSW. Such factors should be considered in future studies that assess the value of regulations involving the discarding of under-size fish.

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Captions to figures

Fig. 1. Diagrammatic representation of: A) the 200 l fibreglass tanks and B) the 200 l tank fitted with the submersible pump assembly used in experiment 1.

Fig. 2. Diagrammatic representation of: A) the aluminium frame and guiding panel, B) aluminium frames containing the fine-meshed polyethelene and C), the frames being rotated together in the treatment tanks (top view) in experiment 1.

Fig. 3. Fish profile and zones used to estimate scale-loss.

Fig. 4. Differences in mean percentage scale-loss (± SE) between the control and treatment fish in experiment 1 for: A) zone no. 1, B) zone no. 2, C) zone no. 3, D) zone no. 4 and E) all zones combined. **significant at P<0.01; *significant at P<0.05.

Fig. 5. Location of lesions from hook damage in treatment fish in experiment 2. n = 40.

Fig. 6. Differences in mean percentage scale-loss (± SE) between the control and treatment fish in experiment 2 for: A) zone no. 1, B) zone no. 2, C) zone no. 3, D) zone no. 4 and E) all zones combined. **significant at P<0.01; *significant at P<0.05.

TABLE 1. - Experiment 1: summaries of F ratios from analyses of variance to determine effects on scale-loss from yellowfin bream due to different treatments of fish (i.e. control vs those fish that passed through the guiding panel), days and tanks. The transforms used to stabilize variances (if required) are also listed. Because 3 fish jumped out of a treatment tank, we substituted means of the remaining replicates and reduced the degrees of freedom accordingly.

Treatment	d.f.	Zone no. 1	Zone no. 2	Zone no. 3	Zone no. 4	All zones
		Arcsin(sqrt (x))	Arcsin(sqrt (x))	Arcsin(sqrt (x))	Arcsin(sqrt (x))	
Treatment of fish (TF)	1	11.25**	0.93	8.21**	3.40	16.91**
Days (D)	4	1.91	0.07	0.61	0.79	0.72
Tanks (T)	6	1.35	1.16	0.96	0.45	0.53
TF x D	4	0.55	1.61	2.74	2.93*	1.53
T x D	23	0.99	1.62	0.78	0.93	1.00
Residual	37					

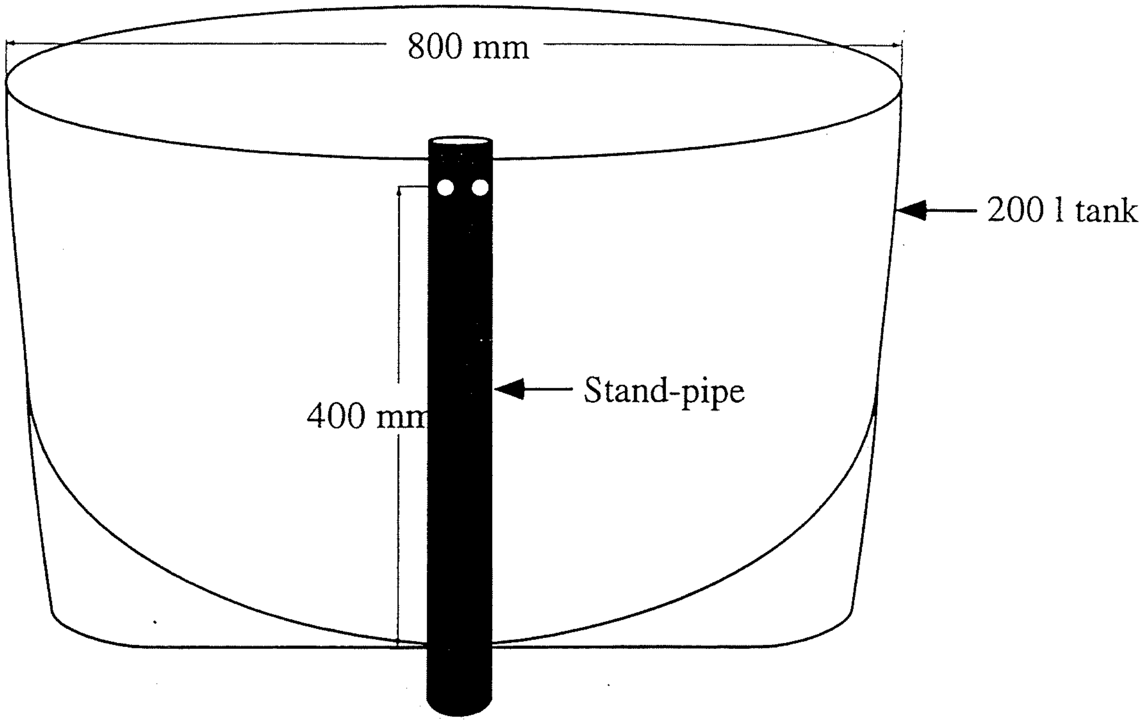
TABLE 2. - Experiment 2: summaries of F ratios from analyses of variance to determine effects on scale-loss from yellowfin bream due to different treatments of fish (i.e. control vs those fish that were hooked), days and tanks. The transforms used to stabilize variances (if required) are also listed. Because 1 fish jumped out of a control tank, we substituted the mean of the remaining replicates and reduced the degrees of freedom accordingly.

Treatment	d.f.	Zone no. 1	Zone no. 2	Zone no. 3	Zone no. 4	All zones
				Arcsin(sqrt (x))	Arcsin(sqrt (x))	Arcsin(sqrt (x))
Treatment of fish (TF)	1	27.59**	13.53**	29.55**	7.69**	56.48**
Days (D)	4	0.92	0.36	2.28	1.83	1.76
Tanks (T)	6	0.92	0.74	0.51	1.28	0.61
TF x D	4	0.66	0.25	3.03*	1.03	2.96*
T x D	24	0.87	0.61	1.06	2.31**	0.65
Residual	39					

TABLE 3 - Summaries of histopathology donc on 2 randomly selected fish from each treatment and control tank in group 2, experiment 2. Fish that died during the experiment are in bold type and fish that survived the experiment are in plain type; (T) treatment tank; (C), control tank; Lengths in centimetres; Scale-loss in percent; (+++, ++, +, 0) severe, high, moderate and none.

Tank no.	Fish no.	Fish length	Day of mortality	Total scale-loss	Diffuse hyperplasia	Focal hyperplasia	Fusion of filaments	Copepods	Cryptocaryon	Blood vessel lesions	Epitheliocystis
T1	**1**	**10.5**	**29**	**10.1**	**++**	**++**	**+**	**++**	**+**	**+**	**0**
T1	**2**	**14**	**30**	**1.5**	**+**	**+++**	**+**	**+**	**++**	**+**	**+**
T2	**1**	**10.5**	**28**	**3**	**+++**	**++**	**+**	**+**	**+**	**+**	**+**
T2	**2**	**10**	**29**	**0**	**++**	**++**	**++**	**+**	**++**	**++**	**+**
T3	**1**	**10**	**39**	**0**	**++**	**++**	**++**	**+**	**0**	**0**	**+**
T3	**2**	**10**	**40**	**0**	**++**	**+++**	**++**	**+**	**++**	**+**	**+**
T4	**1**	**11.5**	**40**	**2**	**++**	**++**	**++**	**+**	**+**	**+**	**+**
T4	**2**	**9.5**	**40**	**0**	**++**	**0**	**0**	**0**	**++**	**0**	**0**
T5	1	10.5	40	0	+	+++	+++	+	+	+	+
T5	2	10	40	0	++	++	+	+	+	+	+
C1	**1**	**10.5**	**37**	**2**	**++**	**++**	**0**	**+**	**+**	**+**	**+**
C1	**2**	**10**	**38**	**0**	**+++**	**++**	**++**	**+**	**+**	**0**	**0**
C2	1	10	40	0	+++	+	+	0	+++	0	0
C2	2	9	40	0	+	++	+	+	+	+	+
C3	1	12	40	0	++	++	++	+	+	+	+
C3	2	8.5	40	0	+	++	++	+	+	0	0
C4	1	8	40	0	+	++	0	0	+	0	+
C4	2	11	40	0	+	+++	++	++	++	0	+
C5	1	9	40	0	+	++	+	++	++	0	+
C5	2	9.5	40	0	+	++	+	+	+	0	0

A) 200 l tank



B) 200 l tank with pump assembly attached

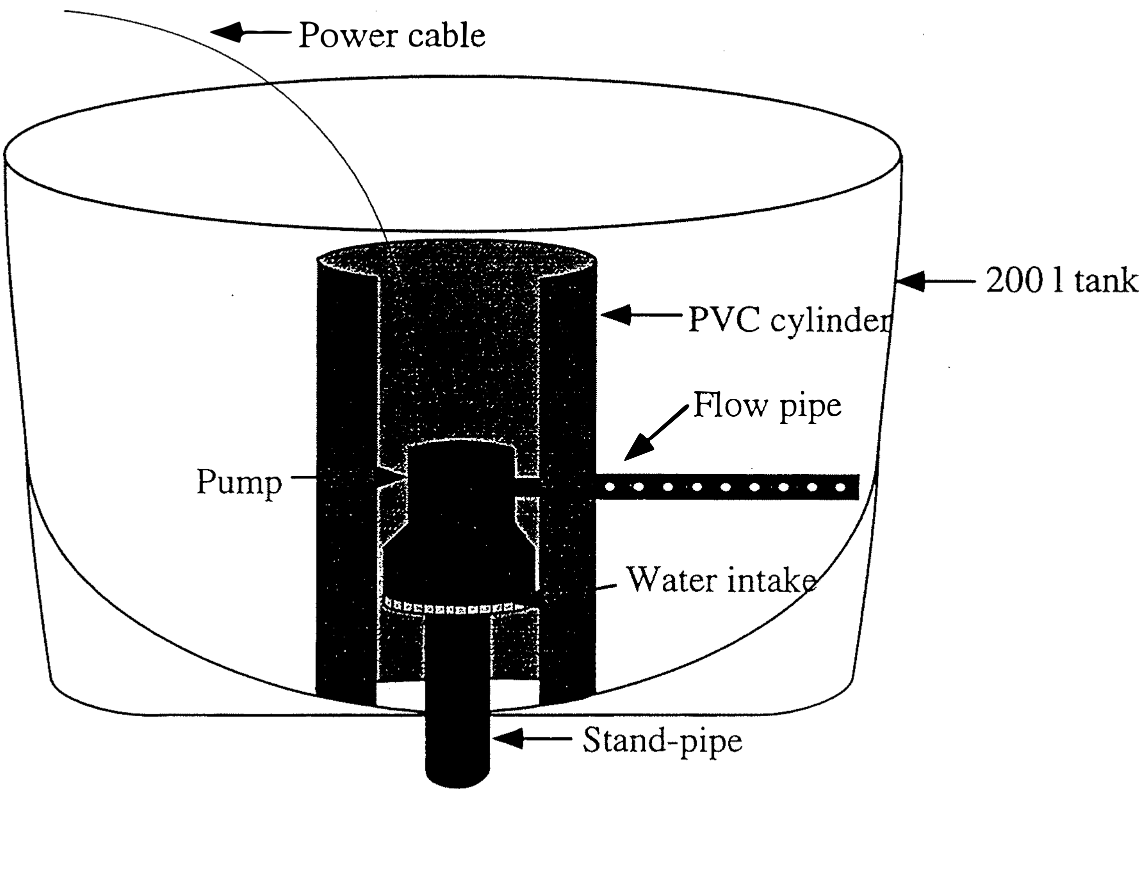


FIG 1

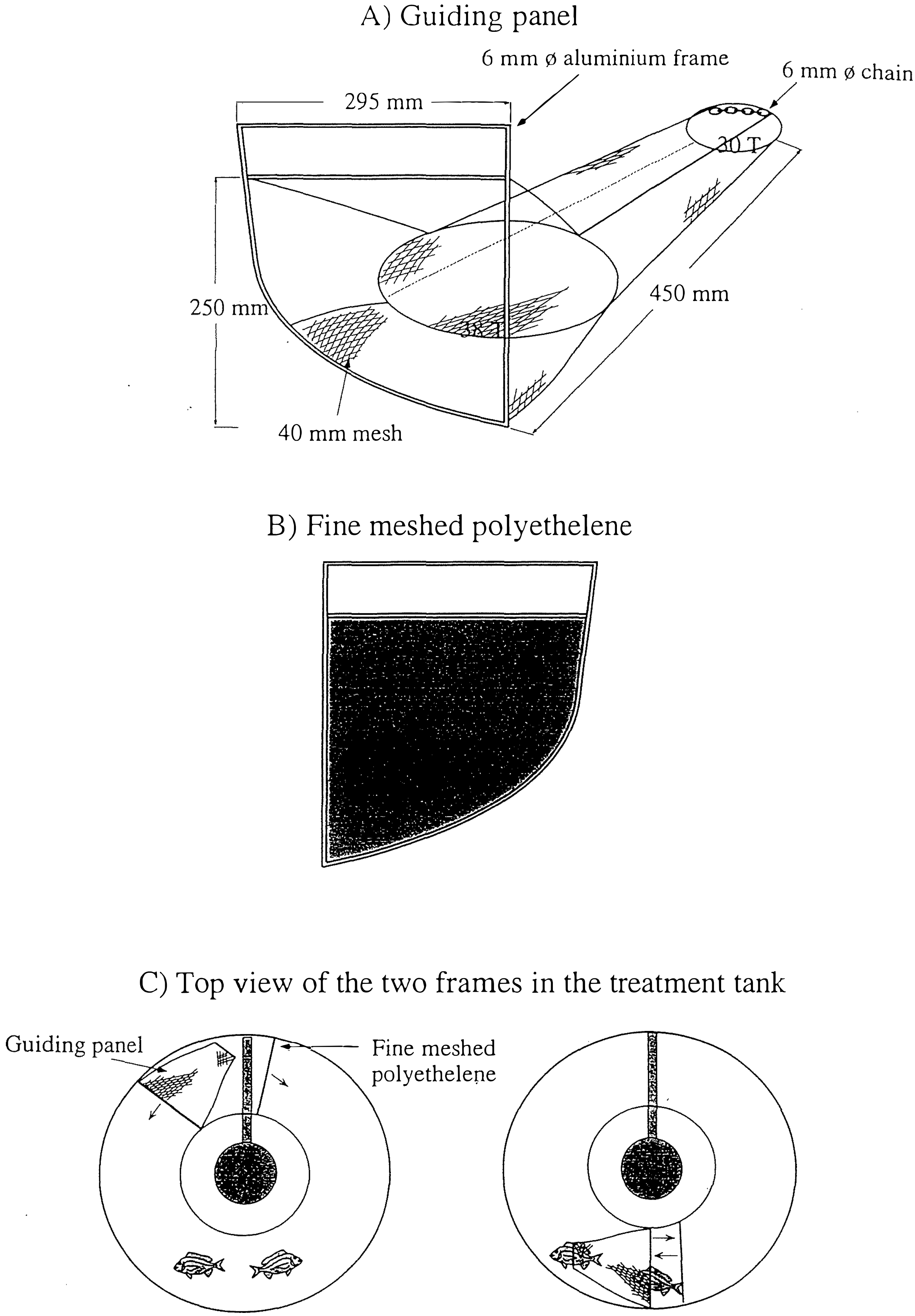

A) Guiding panel
6 mm ø aluminium frame
6 mm ø chain
295 mm
30 T
250 mm
450 mm
3x1
40 mm mesh
B) Fine meshed polyethelene
C) Top view of the two frames in the treatment tank
Guiding panel
Fine meshed
polyethelene

FIG2

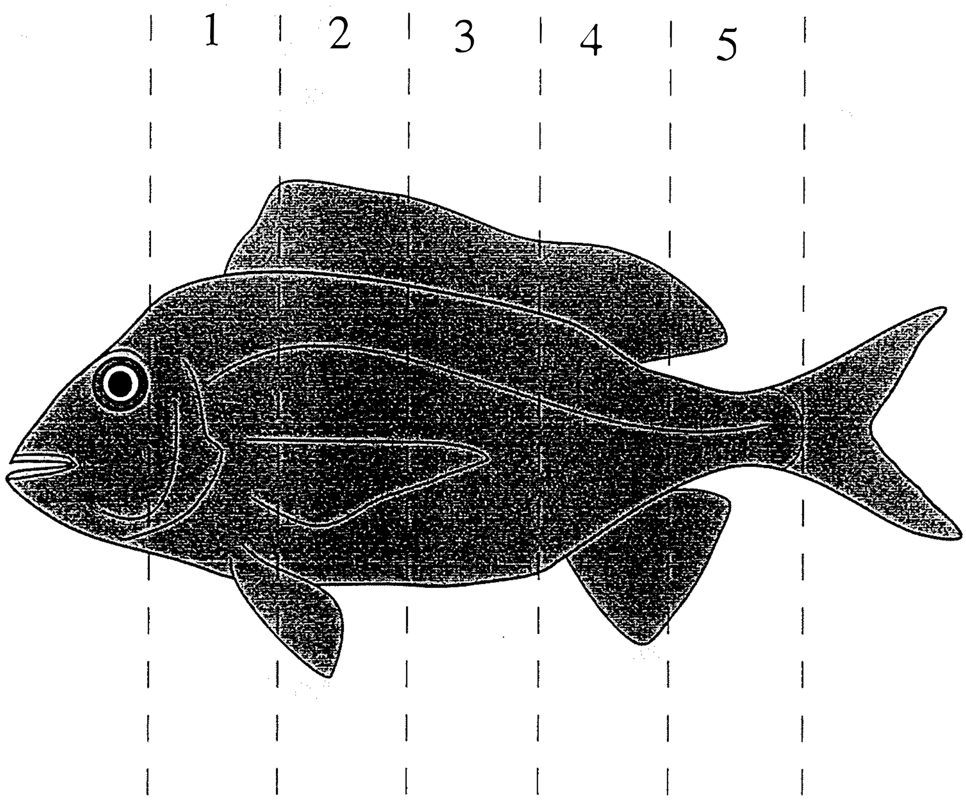


FIG 3

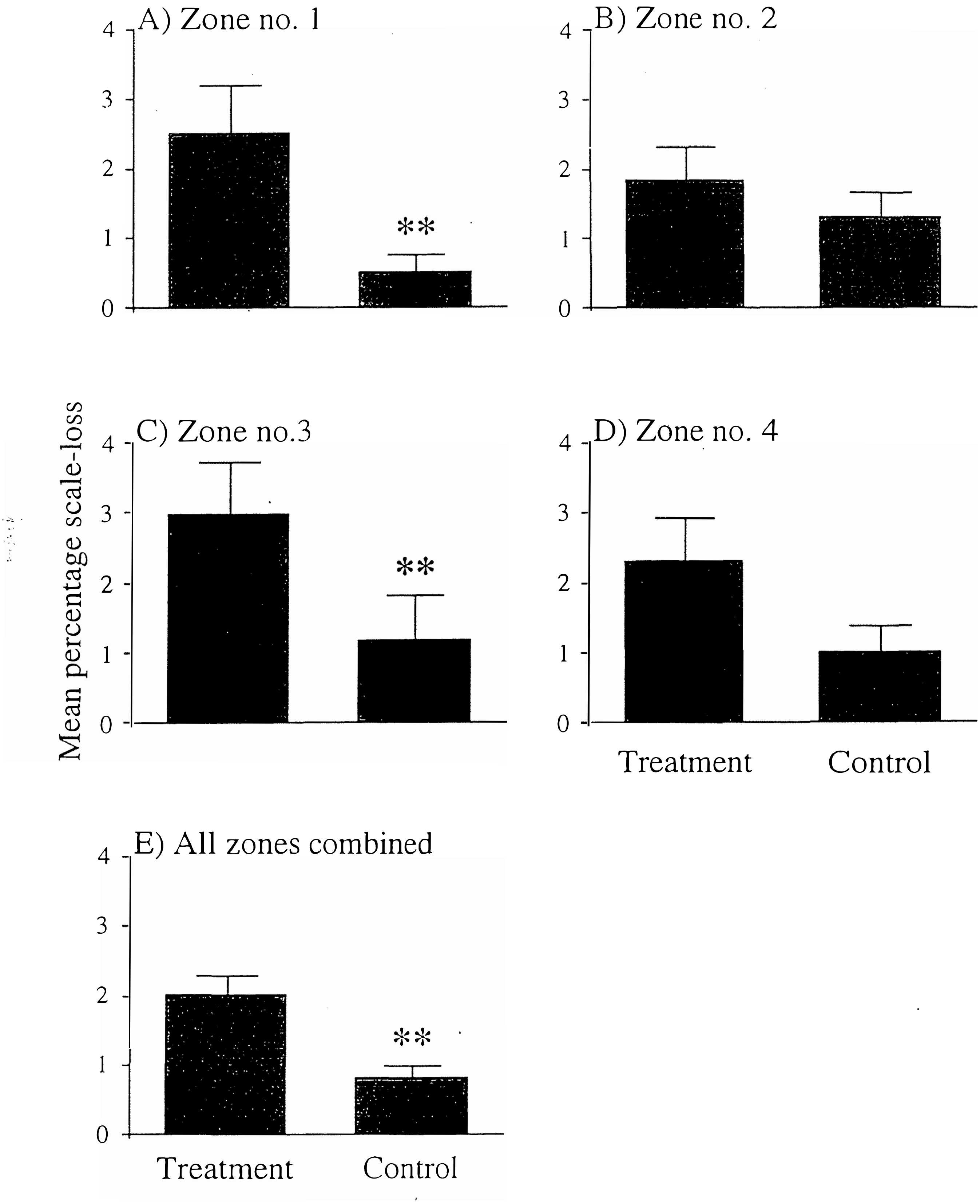
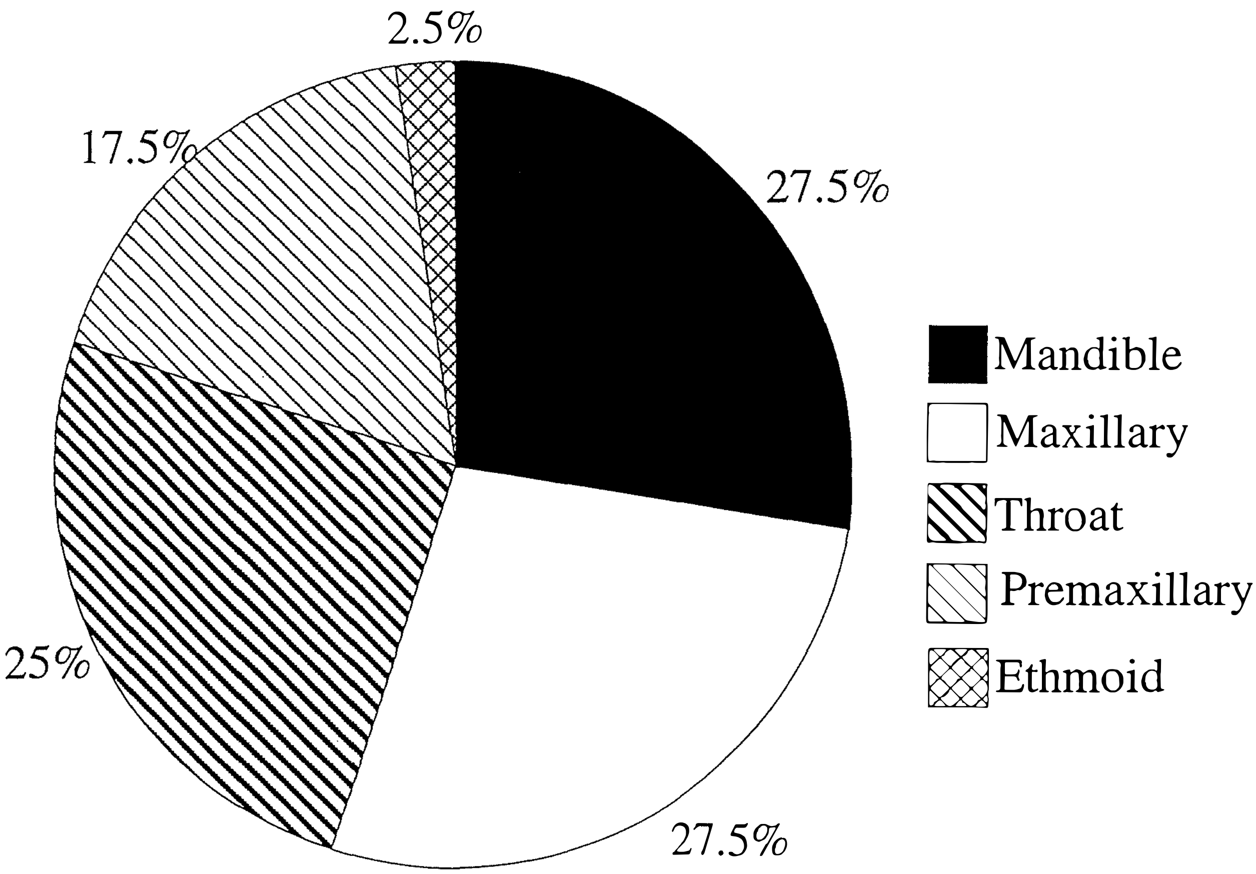

A) Zone no. 1
B) Zone no. 2
C) Zone no.3
D) Zone no. 4
E) All zones combined
Mean percentage scale-loss
0
1
2
3
4
**
Treatment
Control

FIG 4


2.5%
27.5%
17.5%
25%
27.5%
Mandible
Maxillary
Throat
Premaxillary
Ethmoid

F1G5

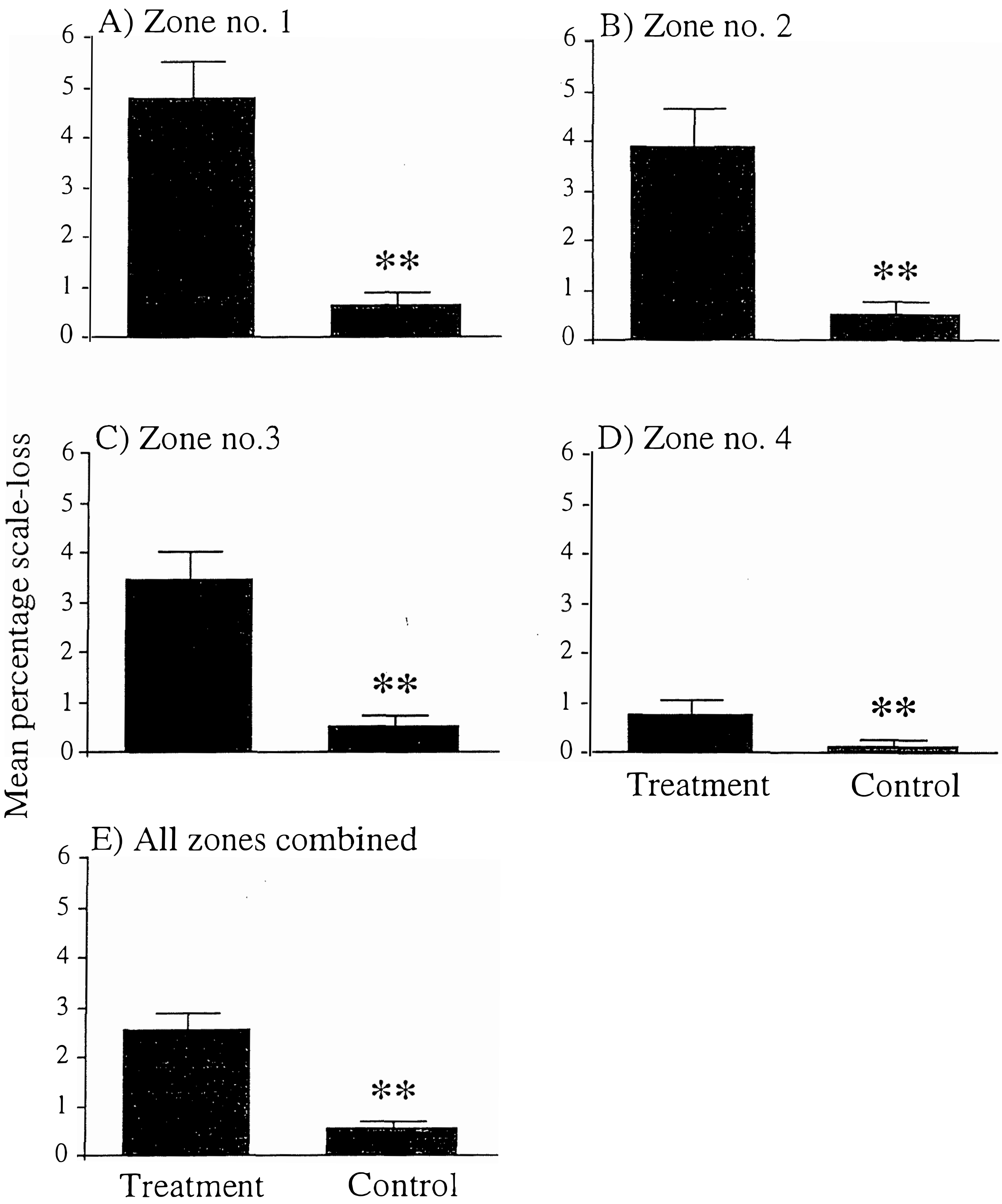

A) Zone no. 1
B) Zone no. 2
C) Zone no.3
D) Zone no. 4
E) All zones combined
Mean percentage scale-loss
0
1
2
3
4
5
6
**
Treatment
Control

FIG 6

Other titles in this series:

No. 1 Andrew, N.L., Graham, K.J., Hodgson, K.E. and Gordon, G.N.G., 1998. Changes after 20 years in relative abundance and size composition of commercial fishes caught during fishery independent surveys on SEF trawl grounds. Final Report to Fisheries Research and Development Corporation. Project no. 96/139.

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No. 3 Stewart, J., Ferrell, D.J. and Andrew, N.L., 1998. Ageing Yellowtail (*Trachurus novaezelandiae*) and Blue Mackerel (*Scomber australasicus*) in New South Wales. Final Report to Fisheries Research and Development Corporation. Project no. 95/151.

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