New Zealand Aquatic
Environment and Biodiversity
Report No. 4
2006
ISSN 1176-9440

Reducing bycatch in New Zealand's scampi trawl fisheries

B. W. Hartill
M. Cryer
A. B. MacDiarmid

Reducing bycatch in New Zealand's scampi trawl fisheries

B. W. Hartill[1]
M. Cryer[1]
A. B. MacDiarmid[2]

[1]NIWA
P O Box 109695
Newmarket
Auckland

[2]NIWA
Private Bag 14901
Wellington

New Zealand Aquatic Environment and Biodiversity Report No. 4
2006

Published by Ministry of Fisheries
Wellington
2006

ISSN 1176-9440

Citation:
Hartill, B.W.; Cryer, N.; MacDiarmid, A.B. (2006).
Reducing bycatch in New Zealand's scampi trawl fisheries.
New Zealand Aquatic Environment and Biodiversity Report No.4 2. 53 p.

This series continues the
Marine Biodiversity Biosecurity Report series
which ceased with No. 7 in February 2005.

EXECUTIVE SUMMARY

Hartill, B.W.; Cryer, M.; MacDiarmid, A.B. (2006). Reducing bycatch in New Zealand's scampi trawl fisheries.

***New Zealand Aquatic Environment and Biodiversity Report No. 4.* 53 p.**

An international compilation of bycatch estimates from a wide range of fisheries has shown that bycatch rates for crustaceans (especially shrimp and prawn) are generally higher in trawl fisheries than in other fisheries. This trend is also evident in New Zealand, where observed catch data from a range of trawl fisheries suggests that scampi (*Metanephrops challengeri*) trawling generally results in high bycatch rates, both in terms of numbers and weight of non-target species caught. This report describes and assesses possible means of reducing bycatch in New Zealand trawl fisheries for scampi. Previous scampi bycatch reduction studies conducted in New Zealand are presented and discussed alongside relevant literature from overseas fisheries.

A wide variety of bycatch reduction methods has been tested in overseas crustacean trawl fisheries, and some have been adopted in commercial fisheries. Two broad approaches are evident, changes in mesh size and inclusion in trawl nets of various devices that exploit behavioural traits of unwanted bycatch species to facilitate their ejection or escape. Methods include the use of square mesh panels in extension pieces or codends, horizontal separator panels, release panels and windows, sorting grids, sloping mesh panels, and electrified trawls. Some of these approaches appear more promising than others, especially the use of appropriate mesh sizes and square mesh panels.

In 1992 the efficiency of configurations of Nordmøre grids incorporated into the port net of a twin-rigged scampi trawl were assessed in the western Bay of Plenty. Catch passing through the grid entered a primary codend, whereas that diverted to an escape panel by the grid, was retained by a secondary codend. Escapees from both codends were retained by fine-meshed covers. Three different bar spacings and three different angles of attack were trialled for the grid, but these had no apparent effect on the proportion of the bycatch retained by the primary codend. Overall, the Nordmøre grid reduced the bycatch of nine large (over 400 mm) commercial species by 83% (by weight, range 55–100% according to species) and smaller species (20–400 mm) by about 30%, but also resulted in a 13% reduction in the weight of scampi caught. Larger, more valuable scampi were preferentially ejected by the grid, and an estimated 15% of the value of the catch was lost.

A mesh selectivity study conducted on the same Bay of Plenty grounds in 1996 examined the selectivity characteristics (for scampi and common bycatch species) of two main net (wings and body) mesh sizes (80 and 100 mm), and three codend mesh sizes (30, 55, and 65 mm). Codend selectivity curves were estimated using 12 mm mesh covers for the six most abundant species caught: scampi, silver roughy, javelinfish, "other rattails", sea perch, and capro dory. These are some of the smaller species caught, and larger species such as hoki, gemfish, and ling, were almost entirely retained by all codends. Codends made of fine mesh retained more small fish than those made of coarser mesh. The 65 mm mesh codend, in particular, allowed many small rattails through to the codend cover. The two finer codend meshes fully retained smaller silver roughy, sea perch, and capro dories, but the 65 mm codend mesh allowed a few to pass through to the cover. All three codends retained almost all of the common scampi length classes, and the size distribution of the catch is likely to be related to emergence from burrows rather than net selectivity.

Estimation of the selectivity at length of the 80 and 100 mm main net meshes was not possible because of the lack of contrast in the length frequency distributions of common species. However, significantly higher catch rates of scampi and sea perch were achieved using the smaller 80 mm mesh, suggesting that the use of 80 mm mesh may reduce both the amount of fishing effort required to catch a given quota of scampi and the total bycatch. Incidental effects such as habitat modification are also likely to be reduced due to the reduction in fishing effort. Recommendations for suitable approaches to reducing the bycatch of non-target fish catch in the New Zealand scampi fishery are outlined.

1. INTRODUCTION

Annual reported landings from New Zealand scampi fisheries (*Metanephrops challengeri*, Balss) have been about 900 t since 1992–93 (Annala et al. 2004). Most of the catch is exported and has a wholesale value approaching NZ$30M. There is a substantial bycatch of finfish managed under the Quota Management System (QMS) that is landed, and a larger bycatch of (mostly small) non-QMS finfish that is mostly discarded on the grounds. The amount of fish discarded is not unusual for a crustacean fishery, but would still put the New Zealand scampi fishery in the top 20 of those discarding the greatest proportions (by weight) (Alverson et al. 1994). Non-QMS bycatch varies considerably in amount and composition, both among Quota Management Areas (QMAs; Figure 1) and with time. At least 50 different species have been recorded by Ministry of Fisheries observers (Cryer et al. 1999, Cryer & Coburn 2000), and the weight of fish bycatch is usually several times the weight of scampi catch (Anderson 2003). This is of continuing concern to the industry, because bycatch increases processing times (Briggs 1986) and may damage the catch (Salini et al. 2000), to managers, because of the difficulties inherent in managing multi-species fisheries (Hongskul 1979, Caddy 1996, Welcomme 1999), and to the conservation lobby because of a perceived high impact of this fishery on the biodiversity and populations of mid-slope benthic faunas and demersal fish species (Bartley 1998a, 1998b). Reducing bycatch in this fishery would, therefore, seem to meet the goals and aspirations of all sectors.

A compilation of estimates of bycatch from a wide range of fisheries by FAO (Alverson et al. 1994) suggested that bycatch rates from shrimp and prawn trawls are generally higher than in other fisheries. Recent New Zealand studies (Anderson et al. 2000, 2001, Anderson 2003) reported similar discard rates in some New Zealand fisheries; for every kilogram of scampi caught, an average of 3.5 kg of fish is discarded, higher than in any other fishery in these studies (jack mackerel, 0.12 kg; arrow squid, 0.14 kg; orange roughy, 0.06 kg; hoki, 0.05 kg; and southern blue whiting, 0.02 kg). Further, scampi trawls tend to contain more bycatch species than finfish trawls (Figure 2), suggesting that scampi trawling is less selective than fish trawling.

Scaling Anderson's (2003) figures to the total reported landings suggests that the annual weight of fish discarded by the scampi fishery (over 3000 t) is much greater than that discarded by the orange roughy and southern blue whiting fisheries (about 1000 t), is comparable with that discarded by the squid and jack mackerel fisheries (3000–5000 t), and is overshadowed only by that discarded by the hoki fishery (over 10 000 t). In some areas, trawling for scampi is also the most prevalent method; a detailed examination of trawl effort in the Bay of Plenty at 300–600 m depth (Cryer & Hartill 2002) showed that, since 1989, the number of scampi tows has far exceeded the number of tows for any other species.

The mortality rates of fish and invertebrates discarded by New Zealand scampi trawlers are unknown, but a priori we would expect them to be high. When invertebrate bycatch from relatively shallow European *Nephrops* trawl fisheries was examined for damage, hard shelled species such as bivalves and crabs sustained fewer injuries than species such as brittle stars and squat lobsters (queen scallops (2%), crabs (14%), starfish (56%), squat lobsters (57%), and brittle stars (100%) (Bergmann et al. 2002). However, obvious damage is only one indicator of likely mortality. Species that do not sink rapidly when discarded are exposed to predation by seabirds and other pelagic predators. Estimates of the availability of trawl discards to seabirds range widely from 14%, for Australian prawn trawl fisheries (Hill & Wassenberg 2000) to over 70% for North Sea *Nephrops* fisheries (Evans et al. 1994), largely as a result of differences in the species composition of the bycatch. Even animals that survive capture and processing to return to the seabed alive are likely to suffer further mortality through injury, stress, displacement from their preferred habitat, and short-term vulnerability to scavengers. Discard mortality rates might be expected to be higher in deepwater fisheries such as New Zealand's scampi fishery because of the greater pressure and temperature changes, and the greater exposure to pelagic predators during sinking.

Given the high level of bycatch in the New Zealand scampi fishery, the likely high mortality of discards (both direct and indirect), and the availability of local and overseas data on methods of reducing bycatch, the Ministry of Fisheries commissioned preliminary work to "scope" the issue. The overall objective of this study was "*To describe and assess means of reducing bycatch in trawl fisheries for scampi.*". Two specific objectives were stipulated, "*To collate and document previous work on gear selectivity and bycatch reduction in the New Zealand and European scampi fisheries for reducing non-target fish catch*" and "*To recommend performance standards, including recommending the design of field gear trials if required, to achieve reductions in non-target fish catch at a variety of levels in the New Zealand scampi fishery*". We used a three-stage process.

First, we collated and reviewed the international literature on methods of reducing bycatch in crustacean trawl fisheries. Many approaches have been tested and we considered the applicability of each to New Zealand fisheries. In doing so, we had to assume some likely bycatch management aims for the fishery. A review of bycatch reduction practices and technology, relating generally to New Zealand trawl fisheries (Booth et al. 2002) is recommended reading.

Second, we reviewed and analysed data from New Zealand studies. Two formal trials have been conducted, both in the Bay of Plenty. The first was an appraisal of Nordmøre grids in 1992, and the second was a study of selectivity characteristics of different codend and main-net meshes in 1996. Other informal trials have been conducted by fishers. We discuss some of these, but no data are available for analysis.

Third, we developed recommendations on future approaches to reducing bycatch in the New Zealand scampi fishery, including some general thoughts on the experimental design of field trials. Our discussions with fishers and overseas researchers suggest that it is essential that industry is fully involved in the development of practical and effective gear, but all stakeholders should be involved in the development of management aims for the fishery, including bycatch management.

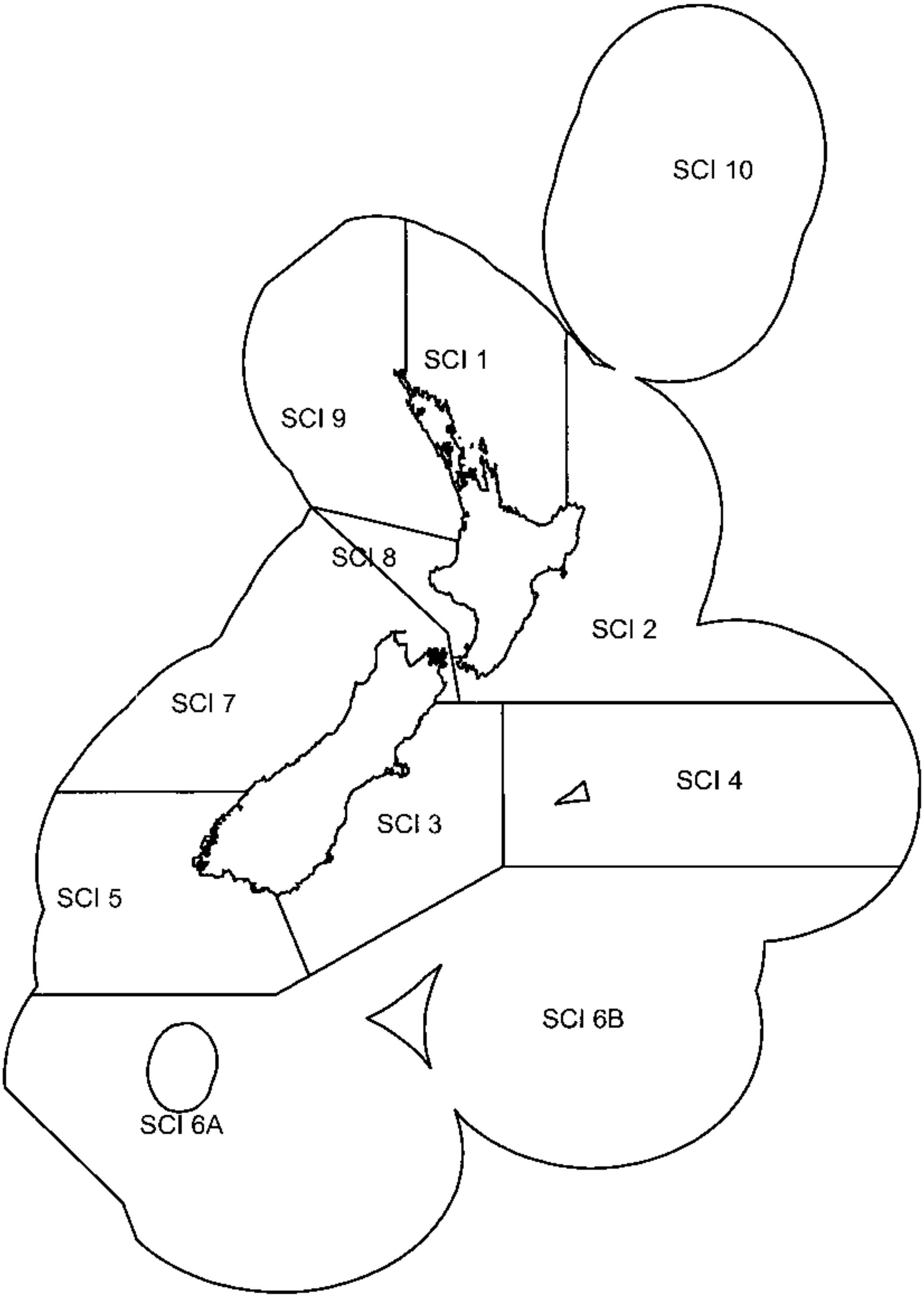


Figure 1: Fishery management areas for scampi in New Zealand as of 1 October 2003. SCI 6A was a separate regulated management area containing all waters within 50 nautical miles of the Auckland Islands. Management areas 3, 4, and 6A were substantially changed when scampi was introduced to the QMS in 2004.

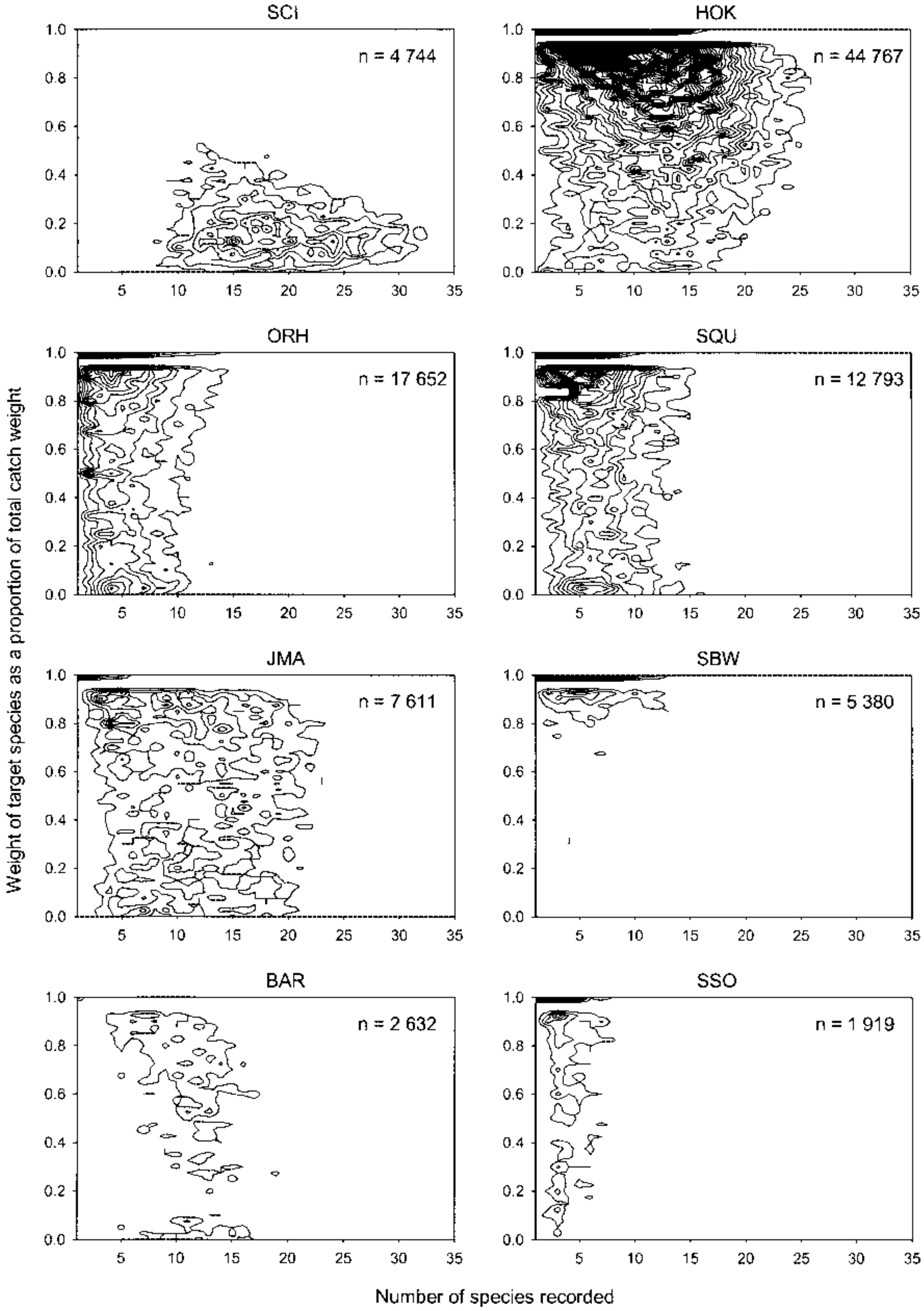


Figure 2: Contour plots of the number of species caught in a tow against the proportion by weight of the target species in that tow. Data from Ministry of Fisheries observers on board trawlers fishing for scampi (SCI), hoki (HOK), orange roughy (ORH), arrow squid (SQU), jack mackerels (JMA), southern blue whiting (SBW), barracouta (BAR), and smooth oreo (SSO). Contours show multiples of five tows, and the relative density of contours generally reflects the number of observations (n). Discontinuities in those parts of the plots corresponding to target catches of 95% or more are probably artefacts caused by poor reporting of very low proportions of bycatch.

2. METHODS OF REDUCING BYCATCH IN CRUSTACEAN FISHERIES

2.1 Overview

The depth at which New Zealand scampi are found (300–500 m) suggests that some form of otter trawling (Figure 3) is likely to be the most practical method of taking this species commercially. In Scotland and Iceland, some scampi are caught in shallow waters using pots, especially in sheltered lochs. However, two trials carried out in the 1990s in the Bay of Plenty and off the Wairarapa coast yielded only hagfish, and the method appears unsuitable for New Zealand scampi.

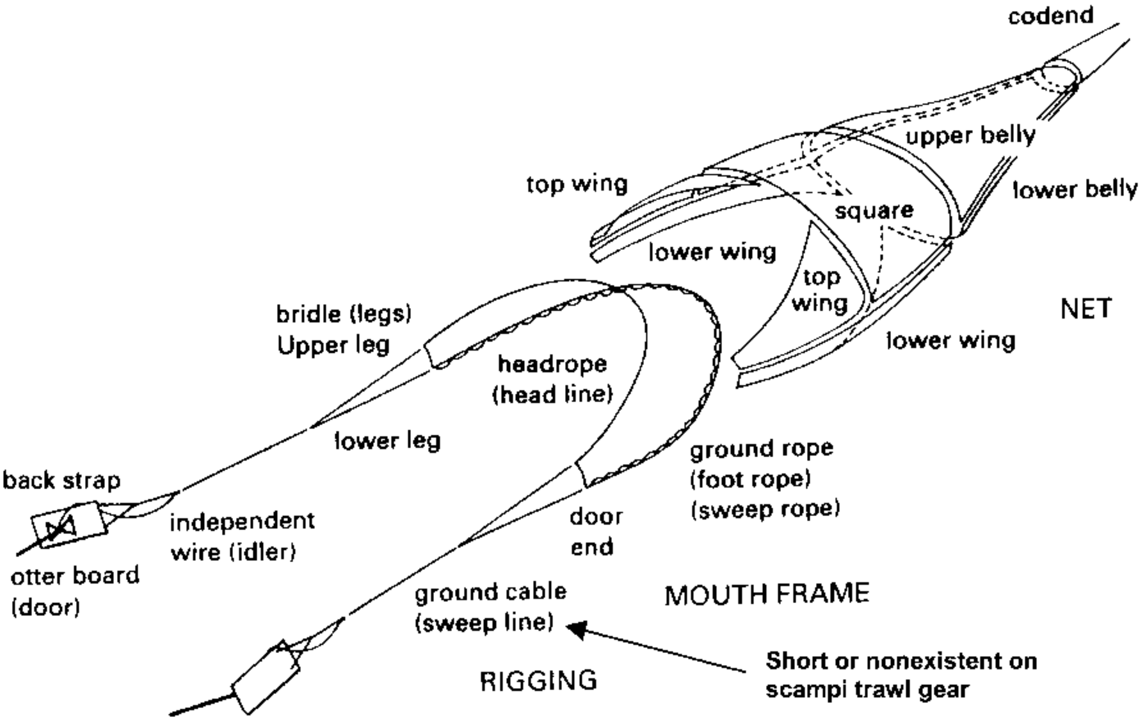


Figure 3: Diagram of a typical bottom otter trawl similar to those used in New Zealand finfish fisheries (after Sainsbury 1996). Scampi trawls typically have no sweeps and the nets are connected by very short bridles directly to the doors. All New Zealand scampi fishers use two or three nets towed together (see Figure 4).

The adoption of twin- and triple-rigged trawls (Figure 4) in the New Zealand scampi fishery to reduce headline height, the removal of fish-herding "sweeps" (Andrew et al. 1991), and generally increasing mesh sizes are all likely to have reduced bycatch, especially of small fish. However, trawling for scampi still catches much fish of little or no commercial value that is discarded on the grounds. Further, it is increasingly accepted that trawling can substantially modify benthic communities, possibly with knock-on effects for stock productivity (Jennings et al. 2001, 2002), so there could be multiple benefits of reducing bycatch or fishing effort. In this section we discuss and evaluate different bycatch reducing gear developed for scampi and prawn fisheries.

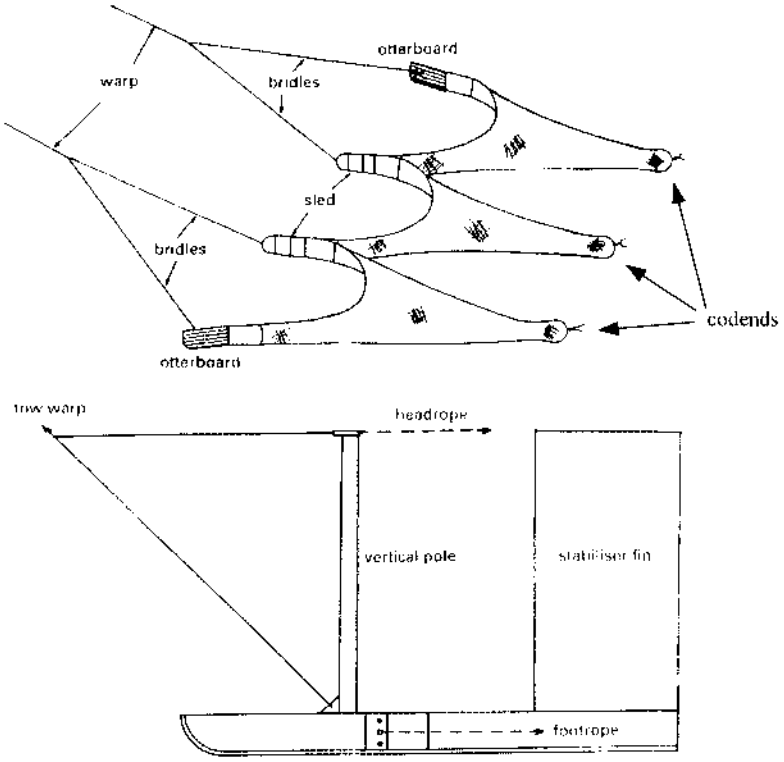


Figure 4: Diagrams of a typical triple rig otter trawl similar to those used in New Zealand scampi fisheries (top) and of a sled (bottom) (after Sainsbury 1996). Some New Zealand fishers use twin rigs with one or two warps.

2.2 Mesh size

There have been many overseas studies on the selective properties of different mesh sizes for scampi, although the focus of most has been on scampi itself. Although northern hemisphere fisheries are based on a different species, *Nephrops norvegicus*, the morphology and size composition of this species is broadly similar to the New Zealand species *Metanephrops challengeri* (Yaldwyn 1954, Robertson & Shanks 1987, Howard 1989, Kirkegaard et al. 1989, Campos et al. 2003). The three Australian species of scampi (*Metanephrops* spp.) are even more similar to *M. challengeri*, and are found in similarly deep water, but most work on bycatch reduction in that country has been done on various large prawn species. Because of these similarities, the findings from overseas studies may be relevant to New Zealand fisheries, although developing a practical and effective technique suitable for routine use will require "fine tuning" to local conditions.

Northern hemisphere *Nephrops* fisheries have employed a variety of mesh sizes, depending on the area fished. There has, however, been a general trend in increasing codend mesh size through time. Initially, *Nephrops* was caught using 40–50 mm seine nets adapted to light trawls with the addition of trawl doors (Thomas 1965). In the early 1960s a minimum legal mesh size of 70 mm became more common in Europe, especially in the United Kingdom, where the entire net was constructed using this mesh (Howard 1989). The minimum mesh size permitted on other European fishing grounds has subsequently increased from 60 to 70 mm (Kirkegaard et al. 1989). Since the late 1980s, use of larger meshes in the wings and body of the net has become more common.

Estimates of the length at which 50% retention occurs (L_{50}) derived from the 1996 study in the Bay of Plenty (*Metanephrops*) are within the range of those found in European studies on *Nephrops* (Figure 5). The 56 European L_{50} estimates presented here are taken from 16 studies, conducted between the Mediterranean and the North Sea, using a variety of net configurations, and the range of parameter values for a given mesh size is therefore not surprising (Main & Sangster 1985, Briggs 1986, Robertson et al. 1986, Kirkegaard et al. 1989, Sarda et al. 1993, Campos et al. 2003). This variability supports a recurring theme in many studies, which is the need to tailor fishing gear to a particular fishery. When multiple mesh sizes were compared concurrently for a single fishery, larger meshes usually, but not always, resulted in higher estimates of L_{50}.

The codend meshes used in New Zealand scampi fisheries are generally finer than the European legal minimum (70 mm) despite broadly similar population size compositions. The current New Zealand minimum legal mesh size is 55 mm, although codends are typically constructed out of mesh as large as 65 mm (stretched mesh). Larger codend mesh may result in some loss of marketable scampi, but as the selectivity of mesh sizes larger than 65 mm has not been formally evaluated, this is difficult to predict accurately.

Most mesh selectivity studies have focused on the selective properties of the codend mesh, although our work suggests that the size of mesh used in the main body of the net can also affect scampi catch rates (see Section 3.3.2.2). Although increasing the size of mesh used in the main body of the trawl may increase the proportion of unwanted finfish escaping (e.g. Broadhurst et al. 2002, Sobrino et al. 2000, Stergiou et al. 1997), results in the Bay of Plenty suggest that loss of comparatively passive *swimming scampi may* be even greater than that of bycatch finfish species. Choice of main body mesh may, therefore, be as important as choice of codend mesh.

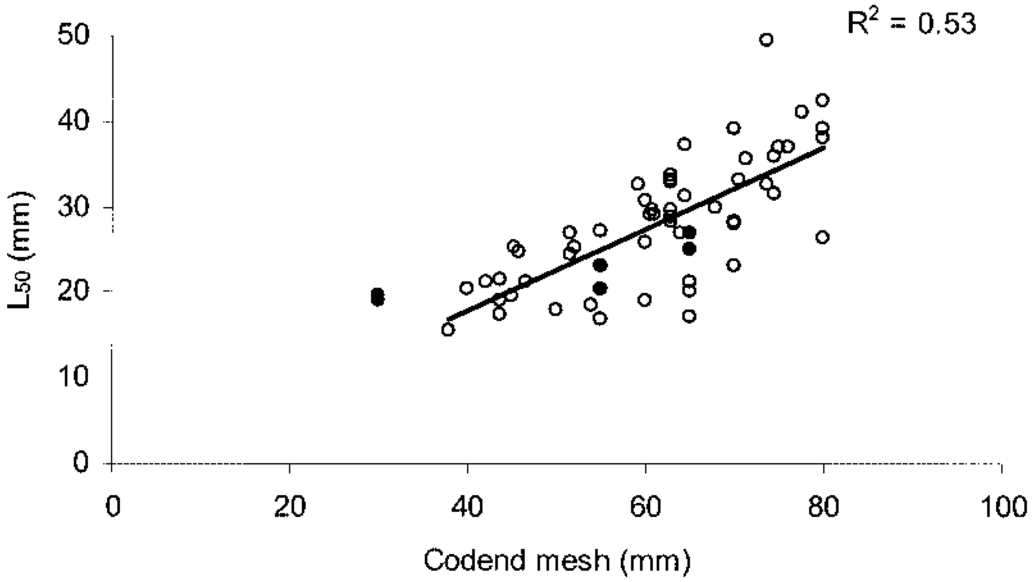


Figure 5: Estimates of L_{50} for codend meshes trialled in European *Nephrops* fisheries (open circles) and in New Zealand in the 1996 Bay of Plenty study (closed circles). The linear relationship between mesh size and L_{50} is derived from the European studies only. All studies were conducted using diamond mesh.

2.3 Use of square mesh in extensions and codends

The codends of trawl nets have historically been constructed of diamond shaped mesh, which has increasingly undesirable properties as the codend lengthens. Drag on a codend increases with increasing catch, and this leads to a narrowing "tunnel" of meshes which progressively "close up" as the drag increases (Robertson 1987). Selectivity, therefore, changes with increasing catch and, in extreme cases where the codend is full or "clogged" with fish, most selectivity occurs in the body of the trawl, rather than in the codend. Similar effects are observed in codends with large numbers of meshes in the circumference. For diamond-shaped meshes, the influence of mesh size, codend diameter and extension length are predicted by the Armstrong Linear Model (Stewart & Galbraith 1989). The selectivity of diamond mesh codends can be improved by shortening the selvedges relative to the number of meshes, giving selectivity properties similar to those of square mesh codends.

Square mesh retains its shape under load and maintains selectivity-at-length because the codend remains cylindrical under load and the meshes remain "open" (Robertson 1987). Codends constructed entirely of square mesh can have problems of their own, however, and Broadhurst et al. (1999) found that an unacceptable number of prawns "leaked" through square mesh codend. Inclusion of diamond mesh panels at the end of the codend overcame this leakage. Initially, square mesh panels were constructed from diamond mesh material mounted on the square (Holt 1895; see Linnane et al. 2000)). However, such knotted material was found to lose its shape following slippage in the knots. Modern, knotless mesh constructed from braided polyamide (PA) or polyethelene (PE) retains its shape much better and also causes less abrasion damage to escaping fish (Linnane et al. 2000). Knotless mesh is comparatively expensive, however, and cannot be repaired quickly using conventional methods.

In the Icelandic shrimp (*Pandalus borealis*) fishery, Thorsteinsson (1992) found that codends constructed entirely of square mesh resulted in reduced catches of undersize shrimp and non-target finfish species, and this gear has been adopted commercially. Inclusion of square mesh panels in codends and extensions constructed primarily of diamond mesh is generally a more promising approach, however (Figures 5 & 6). Trials of composite square mesh codends or extension pieces in the Gulf of St Vincent, Australia, indicated that marked reductions of finfish were possible, but the positioning of the square mesh panels was important (Robertson & Shanks 1994, Broadhurst et al. 1999, Graham & Kynoch 2001). Video footage suggested that, within a trawl, fish generally swam parallel to the side of the net as if attempting to out-swim the gear. At the entrance to the codend, however, the reduction in mesh size and accumulation of catch creates a zone of back-pressure. This back-pressure disrupts the steady swimming of most fish species and elicits more "random" swimming. By carefully positioning a panel of square mesh in the ceiling of the extension piece at this point, fusiform fish can be induced to escape (Broadhurst et al. 2002). If the panel is positioned too far forward, small fish may be prevented from escaping by the high flow rate but, conversely, if the panel is too close to the codend, some of the catch may be lost during hauling. After extensive field trials involving commercial fishers at all stages, square mesh ceiling panels were adopted by the New South Wales offshore prawn fishery (S. Kennelly, NSW State Fisheries, pers. comm.). This may have some relevance for scampi fisheries because both types of fisheries are prone to a substantial bycatch of small fish.

2.4 Horizontal separator panels

In the late 1980s, in the United Kingdom, the use of dual purpose fish/prawn trawls became increasingly common as *Nephrops* fishers took a greater interest in the commercial value of the finfish bycatch. These nets have a 3.5 m headline height and replaced nets similar to those currently used in New Zealand (1.0 m headline height). Unfortunately, the new nets caught large numbers of juvenile finfish, many of commercially important gadoids. Behavioural studies revealed that most fish swam rather high in the net, whereas most *Nephrops* remained close to the seabed (Main & Sangster 1985). This difference was exploited by developing nets divided vertically by a horizontal separator panel 0.75 m above the net belly. These horizontal separators sorted the catch into two codends of differing mesh size (Main & Sangster 1985, Galbraith & Main 1989), the upper one suitable for releasing juvenile fish (90 mm), the lower one suitable for retaining scampi (70 mm) (Engås & West 1995). Because of its superior ability to maintain its shape under tension, square mesh may be a preferable material for constructing horizontal separator panels, as it is less likely to distort the shape of the trawl. Engås & West (1995) used a separator panel of 150 mm square mesh and found 90% of haddock and 72% of saithe in the upper codend. Conversely, 71% of cod were found in the lower codend. In situ video showed haddock and saithe in the lower half of the trawl body tracking upward through the separator panel along its length as they passed towards the codends.

Given the low headline height of nets used in New Zealand, this approach probably has only limited value. However, poor swimmers such as scampi would probably fall through large mesh separator panels, but would have difficulty passing upwards into the top half of the trawl, so the method might work satisfactorily if retention of some of the large QMS bycatch species was commercially justified.

2.5 Release panels and windows

Release panels are sections of the trawl body where there are no meshes, or very large meshes. If the escape panel is on the bottom of the belly, heavy, benthic species are allowed to drop out of the gear before passing to the codend (Fonds 1994). Observations of *Nephrops* in trawl nets have shown that this species tumbles along the belly of the net during towing (like scampi), and release panels on the bottom of the belly are likely to lead to unacceptable losses of scampi.

A more promising release panel approach is the topless trawl, where the entire top section of a low opening trawl is either removed or constructed out of large meshes. This approach has been used to exclude blue cod when targeting flatfish (Crowley 2001), and may be applicable to the scampi fishery, given the poor swimming ability of *Metanephrops*, and the low headline height of nets currently used. Only bycatch of those species with upward escape responses are likely to reduced, however.

Windows, also known as fish eyes or big eyes, are openings in the net ceiling or walls, which are usually held open by frames or hydrodynamic flow (Figures 6 & 7). In 1999, about 30% of the Australian banana prawn fleet used the Bigeye BRD (Robins et al. 1999). Anecdotal evidence suggested that during the daytime, bycatch was reduced by 30–40%, but in turbid waters, or at night, this declined to only 10–15%. Windows may, therefore, be more effective in shallower waters where fish are able to see an opportunity to escape the gear. In the deep water of New Zealand scampi fisheries, there may be insufficient light to guide fish to their escape, unless in conjunction with behavioural response to other aspects of the gear (such as hydrodynamic pressure).

2.6 Sorting grids

The grid system most commonly used in *Nephrops* fisheries appears to be the Nordmøre grid, described by Isaksen et al. (1992). The grid has metal or plastic bars oriented at an angle of about 45° to the tow direction, and the catch is usually directed towards the base of the grid by a mesh funnel sewn into the extension piece. Fish too mobile or too large to pass through the grid escape through an opening at the top of the net, whereas small fish, scampi, and prawns pass through the grid on their way to the codend. The distance between the funnel and the grid, the angle of attack for the grid, and the spacing of bars within the grid are all critical to the system's performance. Slopes shallower than 35° or bars too close together lead to loss of prawns, especially large prawns, whereas slopes steeper than 50° or a funnel set too close to the grid lead to counter productive clogging by skates or flatfish, and concomitant loss of most of the catch.

Use of this system has been compulsory in Norwegian fisheries since the early 1990s and has been tested in some Canadian fisheries (Halliday & Cooper 1999). Grids are used to exclude bycatch from the trawl entirely, or to divert finfish to a separate codend. Hinges have been incorporated into some Nordmøre grids to enable them to be wound onto a net drum (Madsen & Hansen 2001). Nordmøre grids were also adopted in estuarine prawn fisheries in New South Wales, Australia, following studies that demonstrated their efficiency at reducing bycatch of juvenile finfish species (Broadhurst & Kennelly 1996; Broadhurst et al. 1997). Estuarine prawn trawls are comparatively small, and as the largest dimension of the grids used is generally less than 0.5 m, the gear is easily deployed. In offshore fisheries, however, the scale of the trawls necessitates larger grids which are more difficult to deploy and can be dangerous. In New Zealand, informal trials using Nordmøre grids in the early 1990s resulted in two serious injuries (V. Wilkinson, Simunovich Fisheries, now Sanford Ltd, personal communication), suggesting that this method may be unsafe given current practices and, hence, unacceptable to both crews and the Department of Labour (Occupational Safety and Health). However, adoption of Nordmøre grids in the Norwegian scampi fishery suggests that it is possible to employ these grids safely in at least some circumstances.

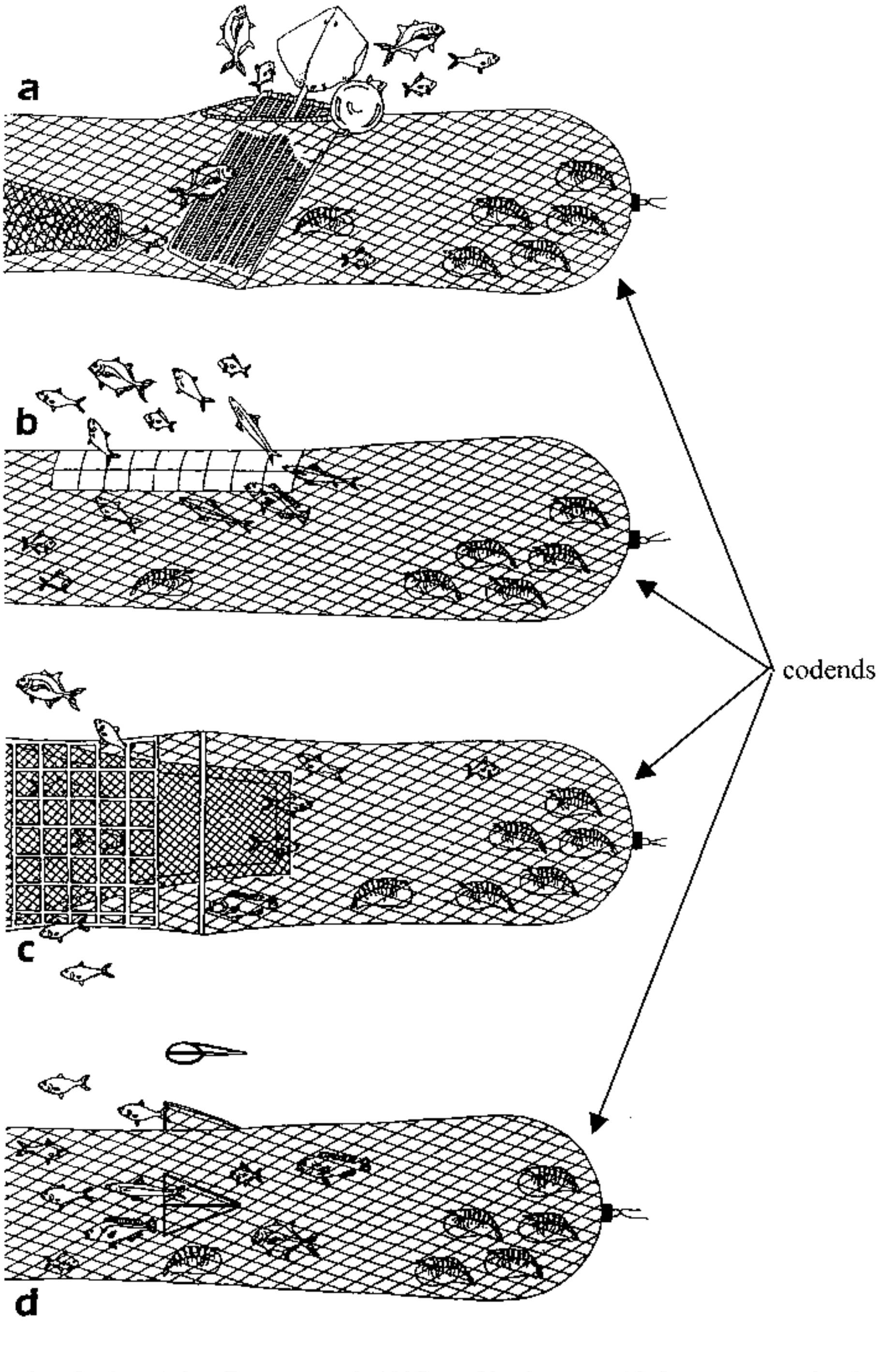


Figure 6: Bycatch reduction devices (after Brewer et al. 1995): a, Nordmøre grid; b, square mesh window; c, radial escape section; d, fisheyes. The prawns shown in these figures can also be thought of as target fish or scampi.

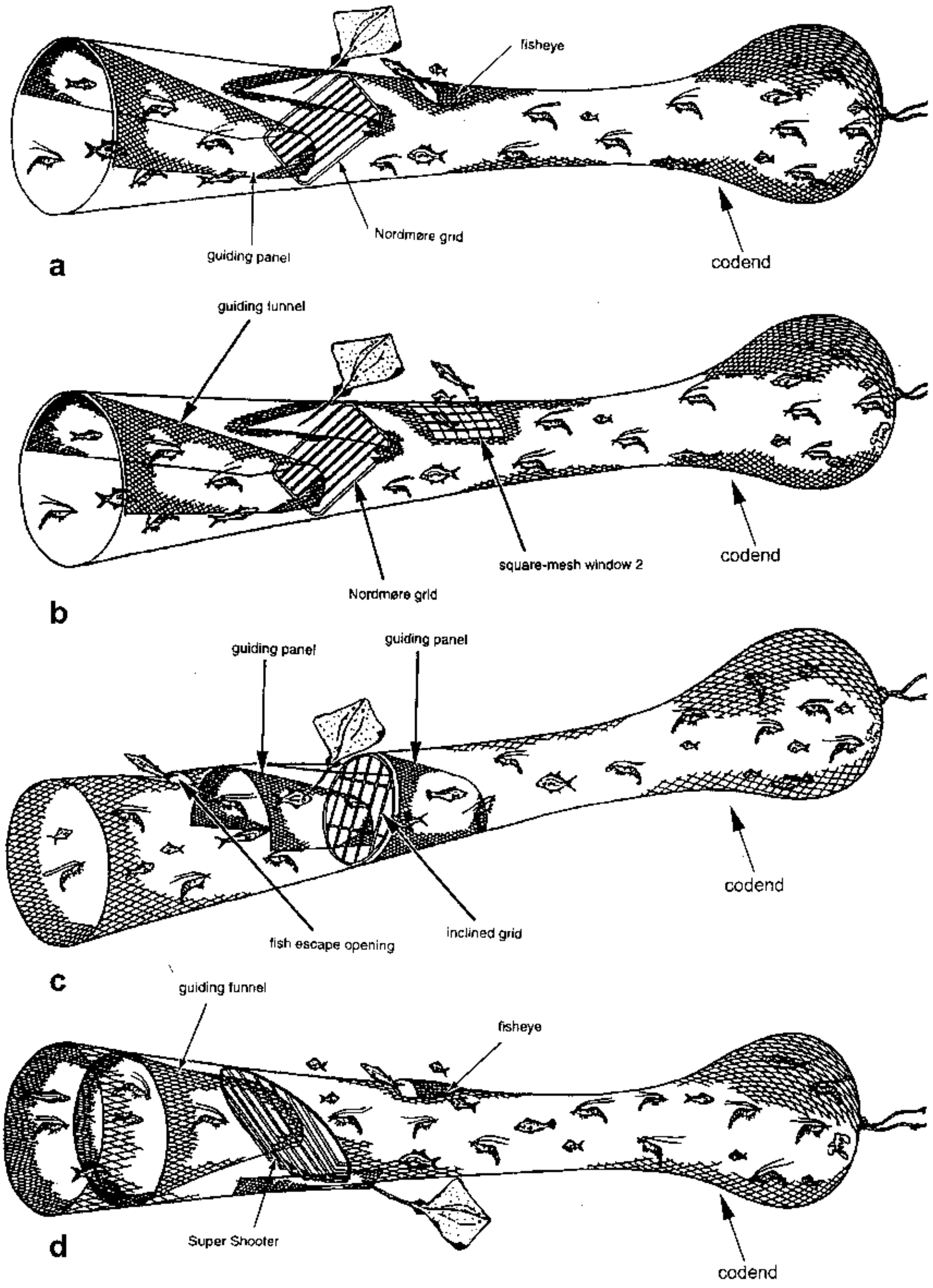


Figure 7: Bycatch reducing devices, after Blaber et al. (1997): a, Nordmøre grid with fish eye; b, Nordmøre grid with dorsal square mesh panel; c, AusTED grid; d, super-shooter grid with fisheye and ventral square mesh panel. The prawns shown in these figures can also be thought of as target fish or scampi.

Many other grid types have been tested, often rigged in conjunction with other bycatch reduction devices (Figures 6 & 7). Specific grids have been designed to exclude particular species, such as turtles, and were sometimes hinged to ease their deployment. When extension pieces are added to a net to allow a grid to be fitted, the resulting loss of tension may result in closed meshes in the extension, which may partially offset gains made by including the grid (Robertson 1987). In the immediate vicinity of a grid, however, the net is supported, and meshes remain open during towing (S. Kennelly, NSW State Fisheries, pers. comm.).

In 1995, NIWA evaluated a Sort-X escape grid (Figure 8) in the Hauraki Gulf, with the intention of improving the selectivity for marketable snapper in the SNA 1 trawl fishery (Ministry of Fisheries project AKSN16). The Sort-X grid proved to be unwieldy, however, and often twisted the codend during trawling. No data were analysed, as this approach was considered not to be a viable option for the snapper fishery. In Norway in 1997, fishing in certain areas is prohibited unless a Sort-X grid is used. Several complaints were made quite soon after its introduction, mostly about crew safety. Thereafter, skippers were given dispensations to stow the grid during bad weather (Isaksen 1997). In the light of these experiences, and because most New Zealand scampi trawlers are small and lack a stern ramp to ease deployment, this approach is not considered feasible.

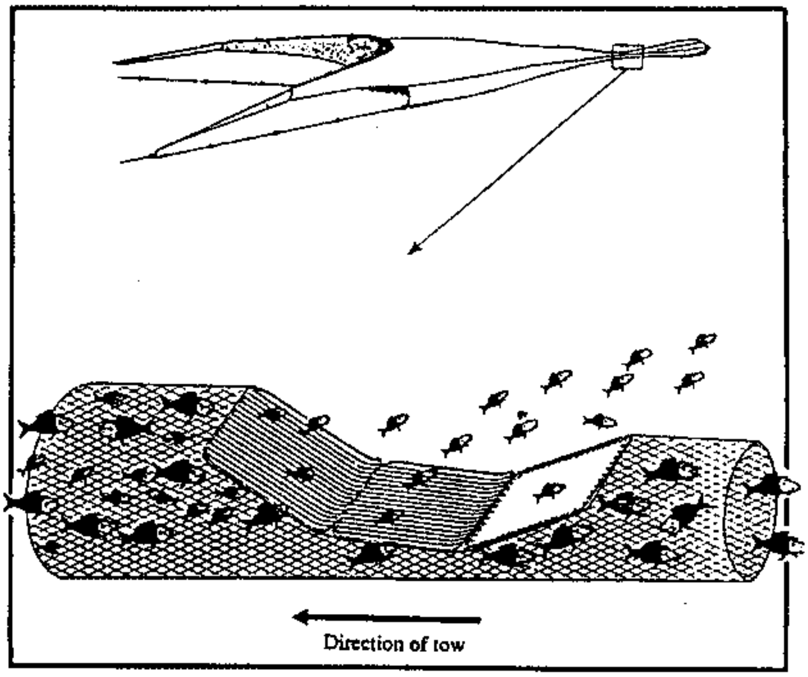


Figure 8: Sort-X escape grid, fitted in the extension piece of a generalised trawl net. Small fish escape through the first two grid sections, whereas marketable fish pass back into the codend. The right hand-panel is made of canvas or nylon.

2.7 Sloping mesh panels

These are rigged in a similar manner to rigid grids, with the intention of diverting finfish upwards, either to escape or to be retained in a separate codend. While "soft grids" present no added complications when retrieving the nets and are less hazardous than metal grids, they can still become clogged by "meshed" fish or masked by skates and rays. Robins-Troeger (1994) evaluated the suitability of a Morrison soft turtle excluder (TED), made from 150 mm monofilament mesh, for reducing bycatch in an Australian prawn fishery. Although catches of juvenile commercial finfish were reduced by about 30%, so were the catches of prawns and marketable crabs. Conversely, when the same device was tested on an offshore prawn fishery, there was no significant loss of eastern king prawns (*Penaeus plebejus*) and invertebrate bycatch, but there was a 32% reduction in the finfish bycatch (Andrew et al. 1993). Before the adoption of Nordmøre grids in Norway (voluntary at first, then by regulation), fishers were obliged to fit sloping mesh panels when certain bycatch ratios were exceeded. These enmeshed panels sometimes burst when certain sizes of red fish (*Sebastes marinus*) became meshed (Isaksen et al. 1992).

2.8 Electrified trawls

In the early 1970s in Europe, field trials of electrified trawls demonstrated that this technology could increase catches of *Nephrops* and sole of marketable size, while reducing catches of juvenile finfish (see Linnane et al. (2000) for review). Trawl nets were electrified via a pulse generator connected by a cable to a capacitor discharge unit, with evenly spaced parallel electrodes on the foot rope. However, because of problems with crew safety, the length of cable required, and animal ethics fieldwork on this approach has ceased. Use of electrified trawls is not considered feasible in New Zealand scampi fisheries due to the depths fished and concomitant technological limitations.

3. NEW ZEALAND STUDIES OF METHODS TO REDUCE BYCATCH

3.1 Overview

Two formal studies of the selectivity characteristics of scampi trawl gear have been conducted in New Zealand, both in the western Bay of Plenty. The first study, in 1992, assessed the extent to which Nordmøre grids could be used to reduce bycatch while maintaining the catch rate of scampi. The second study, in 1996, was designed to estimate the selectivity characteristics of the research trawls used between 1993 and 1995 to estimate relative biomass in QMAs 1 and 2, and to assess the extent to which larger meshes in the body or codend of the trawl might be used to reduce bycatch while maintaining catch rates of scampi. Analyses of both studies are presented here.

Industry has also conducted many informal trials of methods to reduce bycatch, including increasing mesh sizes, modifying nets that the headline does not overhang the groundrope, and various grids in extension pieces before the codend (N. Penwarden, Barine Developments, and V. Wilkinson, Simunovich Fisheries, now Sanford Ltd., pers. comms.). Some of the methods tested (larger mesh sizes and little overhang in the headline) have been adopted operationally by industry, either because they were considered to reduce bycatch without compromising the catch of scampi, or for other reasons. However, no data are available for detailed analysis, and only broad summaries are presented here.

3.2 Nordmøre grid study, 1992

3.2.1 Methods

The experiment was conducted during February 1992 to the east of the Aldermen Islands in the north-western Bay of Plenty, in an area 15 nautical miles (n. mile) from north to south (Lat. 36° 53'S to 37° 08'S) and between 340 and 410 m water depth. This area and depth range was chosen because it had a history of reliable commercial scampi catches.

The start position of each tow was determined by random selection of latitude and depth. Tows were 4.8 n. mile long (2.4 knots for 2 hours) and followed the depth contours that ran roughly north-south. If the start position was 5 n. mile or more from the northern or southern boundary of the study area a northern or southern tow direction was chosen at random. For tow start positions closer than 5 n. mile to a boundary, tow direction was always away from the boundary. A new selection of random trawl positions and directions was made if all tows for a particular treatment were in close proximity or in the same direction. All tows were done between dawn and dusk to reduce the effects of diel changes in catchability of scampi and bycatch species (Vignaux & Gilbert 1993).

The experiment was conducted using a 28 m commercial scampi trawler (*Mutual Enterprise*) deploying twin trawl gear. tHE nets were identical except that the port net was modified to include the Nordmøre grid (Isaksen et al. 1992) as in Figure 9. In front of the main (primary) codend, a welded aluminium grill was laced at an angle across the net throat. An internal, 38 mm mesh funnel led from the net mouth to the base of the grill to accelerate the catch past its face. An equilateral, triangular escape gap was cut in the main body of the net immediately forward of the upper edge of the grill. This gap allowed fish that were diverted upwards by the grill to escape from the main body of the net. These diverted fish were caught in a secondary codend constructed of 100 mm mesh and covered with 38 mm mesh. The rest of the catch passed through the grill and was caught in the primary codend constructed of 50 mm mesh and covered with 38 mm mesh.

Grills of three different bar spacings (50, 55, and 60 mm) and three angles of attack (35, 45, and 55 degrees from horizontal) were tested, giving a total of nine combinations or treatments. Three replicate tows of the same randomly selected treatment were completed on each of nine successive days, making a total of 27 tows. Grills and angles of attack were switched overnight in preparation for the following day's fishing. The catch from each part of the gear was sorted separately (to species where possible) and weighed to the nearest 0.1 kg using motion-compensating scales. The size frequency of scampi and all other species of commercial interest were measured separately for each part of the gear.

All data analysed came from the primary and secondary codends on the port net and their fine-meshed covers. The percentages of each species that passed through the grill and into the primary codend and through to the fine-meshed covers were calculated and arc-sine transformed (Zar 1996). The replicate tows for each of the treatments in the experiment were carried out on a single day. This design was adopted to reduce the number of gear changes and maximise the number of trawls possible. However, this approach means that any difference between treatments may be due to a "day effect" (day-to-day differences in grill efficiency or the behaviour of bycatch or scampi). This was tested by estimating the day effect separately by comparing catches among four days when identical gear configurations were used.

3.2.2 Results

Over all tows, more than 65 species of fish and invertebrates were caught. These ranged in size from small gobies to large sharks and skates (Appendix 1a). The invertebrates comprised mainly echinoids, asteroids, and gastropods. A total of 4497 kg of all species combined was caught by the port net during the experiment. Most of this (83%) was bycatch, indicating that, for every kilogram of scampi caught, 4.8 kg of bycatch was taken. This is consistent with other studies of the bycatch of New Zealand scampi trawlers. The grills were effective in diverting 62% (by weight) of the total catch of the port net into the secondary codend. In the absence of the secondary codend, this bycatch would not have been retained by the trawl gear.

Almost half of the variation in the percentage of catch diverted into the secondary codend was associated with the catch of rough skate (*Raja nasuta*) ($r^2_{adj} = 0.47$, $F_{1,25} = 23.85$, $p << 0.001$). Skates are probably flattened across the grill by water flow and prevent some of the catch from passing through into the primary codend (Figure 10). Because of this effect, the weight of the skate catch in a tow was introduced as a covariate in subsequent analyses of the effects of grill bar spacing and angle of attack.

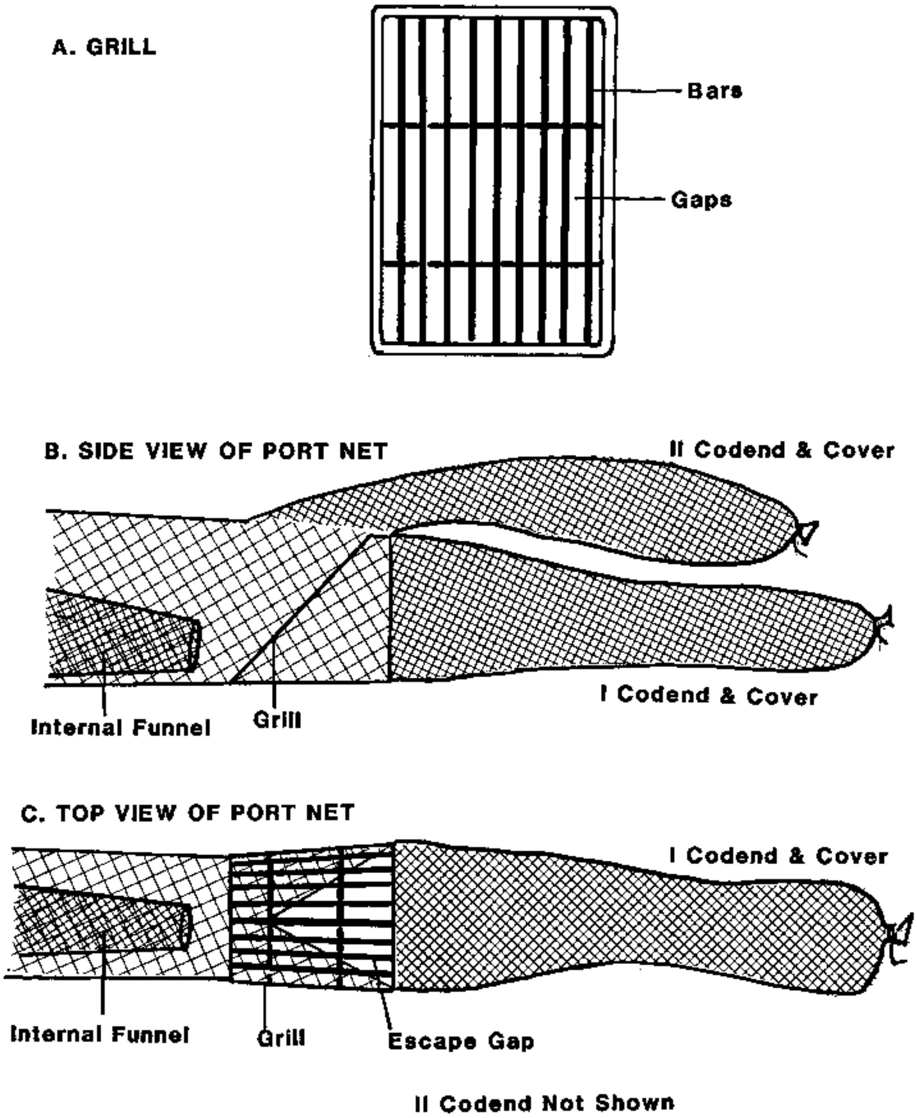


Figure 9: Diagram of the additional elements in the rear of the port net.

Neither grill bar spacing nor angle of attack had any effect on the proportion of total catch (all species combined) diverted to the secondary codend ($F_{8,17} = 0.03$, $p = 0.97$). However, grills were effective in diverting a high percentage (78% by weight) of the larger, commercially important species into the secondary codend. This proportion varied among species, all individuals of six large-bodied species were diverted, whereas lower proportions of red cod and hoki were diverted (Appendix 1b), largely, we suspect, because of the higher proportions of small and juvenile individuals. All grill and angle combinations were equally effective in allowing commercially important fish to escape (all such species, $F_{9,23} = 0.40$, $p = 0.92$; red cod: $F_{10,22} = 0.94$, $p = 0.53$; hoki: $F_{10,23} = 0.54$, $p = 0.83$).

Up to about 20 small-bodied fish species of very little commercial value are commonly caught in scampi trawls (Appendix 1a), including silver roughy (*Hoplostethus mediterraneus),* sea perch (*Helicolenus percoides*, now a QMS species), javelinfish (*Lepidorhynchus denticulatus*), capro dory (*Capromimus abbreviatus*), and sea-urchins (*Phorosoma* spp.). The grills were not very effective in diverting these smaller fish out of the trawl net, and only 33% by weight was found in the secondary codend. The catch of skate in a tow significantly affected the percentage of the total weight of these species diverted to the secondary codend ($F_{1,17} = 13.5$, $p = 0.002$), but grill bar spacing and angle of attack had no additional effect ($F_{8,17} = 0.66$, $p = 0.72$). Restricting the analysis to the most frequently caught small-bodied species (silver roughy and sea perch) showed significant effects of skate ($F_{1,17}$ = 24.05, p <<0.01 and $F_{1,17}$ = 8.39, p = 0.01 respectively) but no effect due to grill bar spacing or angle of attack ($F_{8,17}$ = 0.60, p = 0.76 and $F_{8,17}$ = 0.55, p = 0.80 respectively). There were no significant day effects on the level of catch ($F_{4,11}$ = 3.87, p = 0.058). The largest source of variation was among tows. Post-hoc power analysis suggested that our power to detect a day effect was low, however, because of the high between-tow variation.

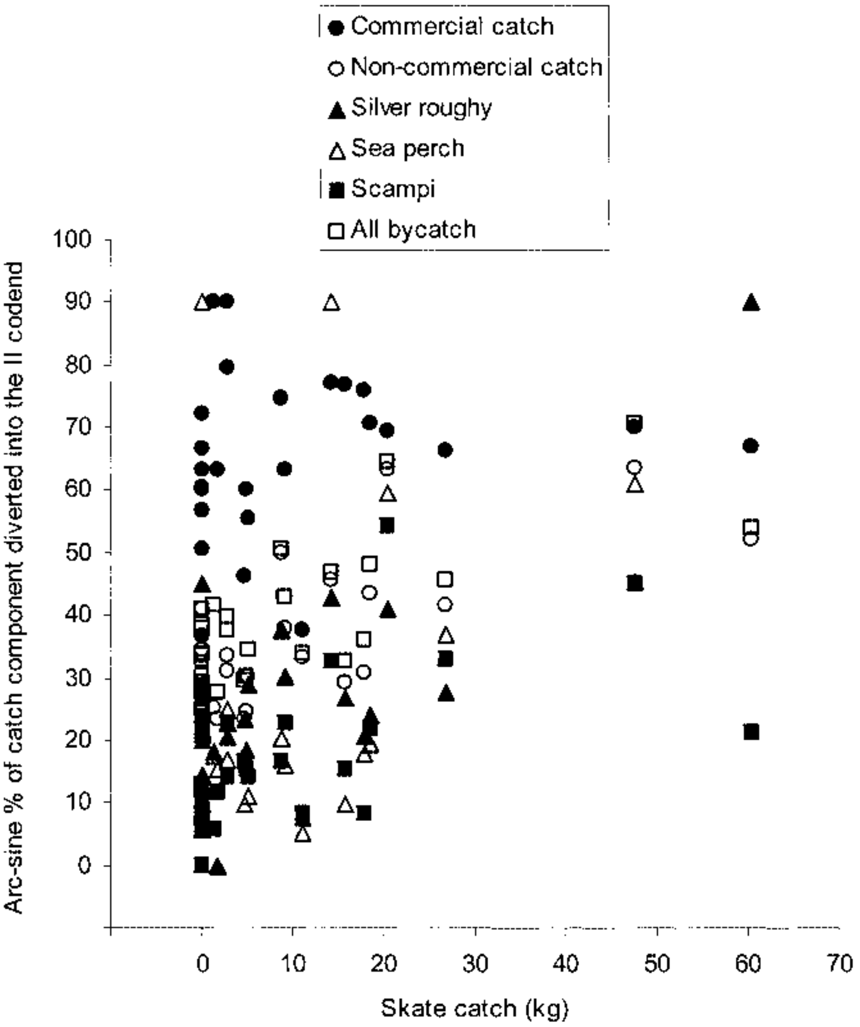


Figure 10: The relationship between skate catch (kg) and the percentage (arc-sine transformed) of different catch components in the port net that were diverted into the secondary codend.

The magnitude of the skate catch was the largest source of variation in the proportion of scampi diverted to the secondary codend (r^2_{adj} = 0.20, $F_{1,25}$ = 7.51, p = 0.01). There were no consistent differences due to spacing of bars on the grills or their angle of attack (Appendices 1c and d) although a post-hoc power analysis suggests that the design had reasonable power (0.84) to detect differences of 12% or more in the mean percentage of scampi diverted to the secondary codend. The percentage of scampi diverted was not affected by the catch of large or small fishes (r^2_{adj} = 0.06, $F_{1,25}$ = 0.11, p = 0.11; r^2_{adj} = 0.02, $F_{1,25}$ = 0.47, p = 0.50). The grills tended to divert larger scampi to the secondary codend; the mean size (orbital carapace length, OCL) of scampi in the primary codend was 39.11 ± 0.05 mm (SE) compared with 40.73 ± 0.13 mm in the secondary codend (Figure 11). Large skate on the grills would tend to mask this effect (diverting all size classes), but excluding stations with a large catch of skate increased the difference only slightly from 1.62 to 1.85 mm (39.07 ± 0.05 mm *vs* 40.92 ± 0.17 mm). Overall, there was a clear trend for increased selectivity of the grills with size; no scampi smaller than 20 mm OCL were diverted whereas up to 20% of scampi larger than 55 m OCL were diverted (Figure 12). Because these larger scampi are more valuable per unit weight than smaller scampi (Appendix 1) the loss in catch value was larger than the loss in catch weight. A simple analysis suggests that about 15% of the overall value of the scampi catch was ejected by the grills (Appendix 1e). Broadhurst (2000) suggested that acceptance of a bycatch reducing system that caused a loss of more than 5% of the catch was likely to be problematic.

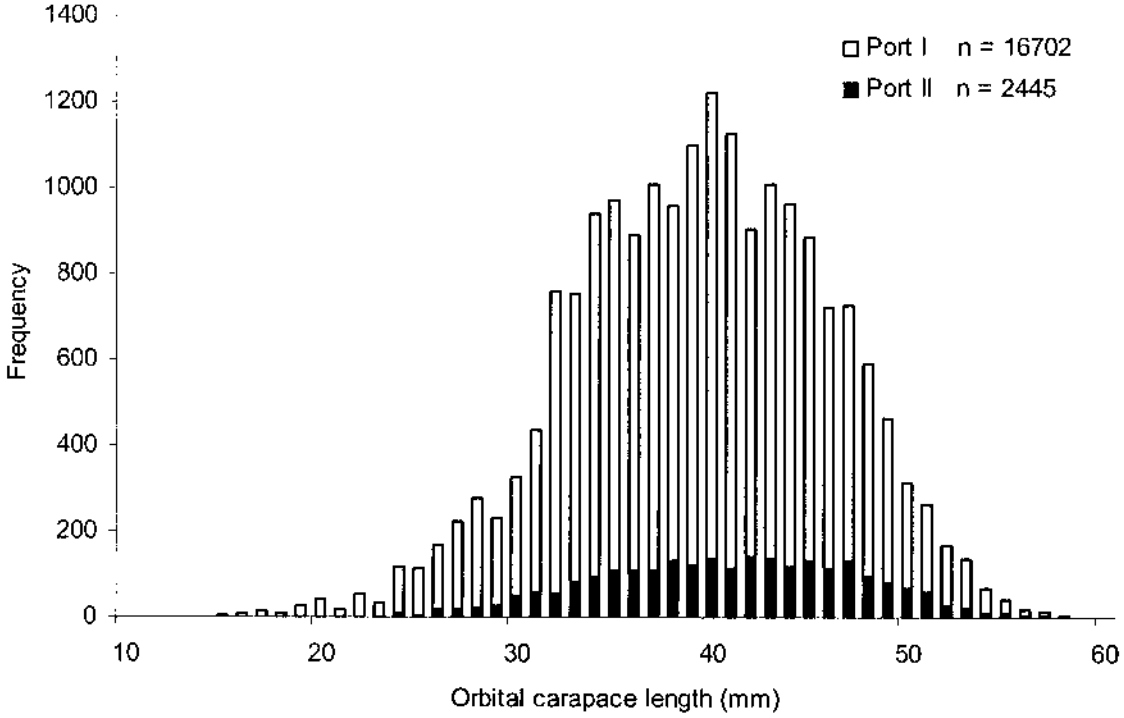


Figure 11: Size frequency of scampi caught in the primary (Port I) and secondary (Port II) codends.

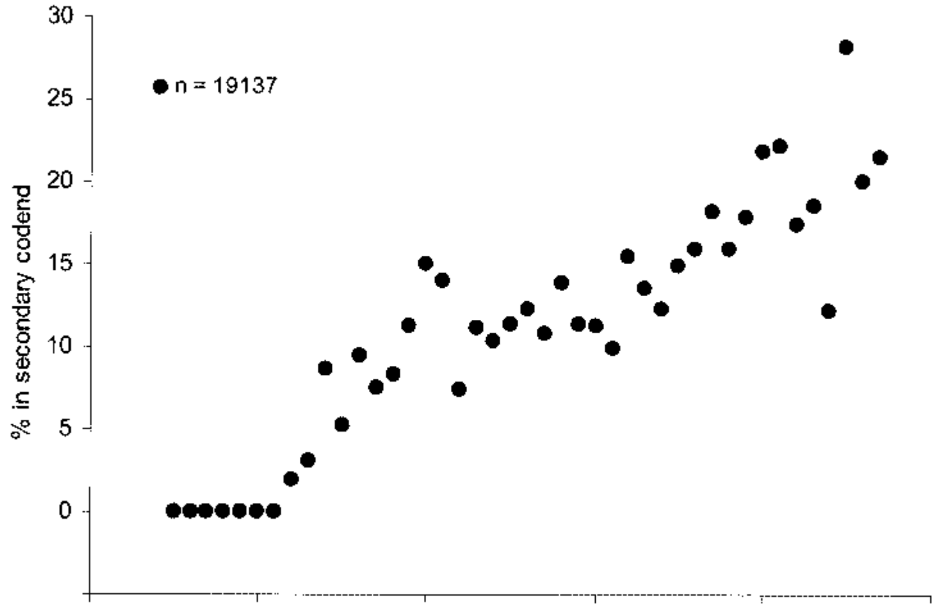


Figure 12: The proportion of scampi diverted into the secondary codend by size class.

As small-bodied fish species make up much of the bycatch of scampi trawlers, a method that reduces their capture would be highly desirable. However, the grills tested in this experiment were not very efficient in reducing small fish bycatch, even though they reduced the bycatch of larger, potentially valuable fish substantially. The codend covers and internal funnel fitted to the experimental grills may have reduced their efficiency, however, especially in combination with the frequent encounters with skates, and this trial should not be taken as a definitive indication that Nordmøre grills are unsuited to New Zealand scampi trawlers. Areas of square mesh panelling in front of the escape gap may assist smaller fish to escape (e.g., Andrew & Pepperell 1992, Broadhurst 2000), and research in the European scampi (*Nephrops norvegicus*) fishery suggests that net modifications can greatly reduce bycatch if they are targeted to the behaviour of the bycatch species (Main & Sangster 1985, Briggs 1986, 1992, Madsen et al. 1999, Madsen & Hansen 2001, Campos & Fonseca 2004).

3.3 Mesh selectivity study, 1996

3.3.1 Methods

3.3.1.1 Fieldwork

In April 1996, NIWA conducted an experiment in the western Bay of Plenty to estimate the selectivity of alternative mesh sizes in the body and wings (100 vs. 80 mm; hereafter referred to as main net mesh) and codend (65 and 55 mm vs. 30 mm) using Florida Flyer gear deployed from the R.V. *Kaharoa* (see Cryer & Stotter (1997) for net plan). Fish passing through codend meshes were retained in a cover constructed of knotless 12 mm mesh. The mesh sizes used for each tow were randomised based on a likely completion of four tows per day; the main net was changed once a day, whereas the codend was changed almost every tow (Table 1). All tows (3.0 nautical miles at a target towing speed of 2.8–3.0 kn) were located within the same 15 nautical mile ribbon. Start positions were determined simply by working north along the ribbon until no further tows could be completed, then turning around and working south. The target depth was 380–400 m.

Four replicate tows were made for each combination of codend (30, 55, and 65 mm stretched mesh) and main net (80 and 100 mm stretched mesh), resulting in 24 valid trawls. It was necessary to repeat many of the tows with the 100 mm trawl because, part-way through the voyage, the net was found to be improperly rigged in the wings (and this can be expected to affect selectivity) (Table 1).

From each tow, both scampi and bycatch were sorted into three subcatches: main net, codend, and codend cover. The main net subcatch included all animals caught up to the headline. Those for the codend and its cover are self-explanatory. Anything falling to the deck through the belly meshes (i.e., aft of the netsonde) was included in the codend subcatch because these animals had already passed the wings and would probably have passed through to the codend. All scampi, QMS fish (as at the time of the experiment in 1996), and large non-QMS species (dories, stargazers, etc.) were weighed directly using motion-compensating "SeaWay" scales. The weight of small bycatch species (roughies, capro dories, Lucifer's dogfish, etc.) was estimated by subsampling and weighing the subsamples using motion-compensating "SeaWay" scales. All scampi were measured (orbital carapace length, OCL, to the nearest whole millimetre below the actual measurement) to a maximum of about 10–12 kg (both sexes combined) for each subcatch. Usually, the entire subcatch was measured. For female scampi, the developmental stages of external eggs and internal gonads were also recorded. All QMS fish from all subcatches were measured to the nearest whole centimetre below the actual measurement and as many non-QMS fish species as possible were measured to the same precision.

Table 1: Station numbers where each replicate tow for a factorial experiment of main net and codend mesh sizes was completed. Repeat tows were necessary because it was discovered that the original 100 mm net had been improperly rigged.

Nominal day	Body mesh (mm)	Codend mesh (mm)	Station number	Repeat station number
1	80	55	18	–
1	80	65	19	–
1	80	30	27	–
1	80	55	28	
2	100	65	23	35
2	100	30	24	36
2	100	55	25	37
2	100	55	26	38
3	80	30	20	–
3	80	55	21	–
3	80	65	22	56
3	80	30	47	–
4	100	30	29	39
4	100	55	30	40
4	100	30	31	41
4	100	65	32	42
5	100	55	33	43
5	100	65	34	44
5	100	30	45	–
5	100	65	46	–
6	80	65	48	–
6	80	65	49	–
6	80	30	50	–
6	80	55	51	–

3.3.1.2 Estimation of codend selectivity

Preliminary analysis revealed that six species were caught in both the codend and codend cover in sufficient numbers to estimate codend selectivity. For each of these species, Richards selection curves (see Wileman et al. 1996) were fitted to the numbers of fish retained in the codend divided by numbers in the codend and cover combined for each (1 cm) length class *i*.

$$r(i) = \left(\frac{\exp(a + bi)}{1 + \exp(a + bi)} \right)^{1/\delta}$$

where the parameters *a* and *b* describe a logistic curve, with an asymmetry parameter δ. A bootstrap approach was used to estimate variance because it allows between-tow variability and subsampling (frequently necessary for small bycatch species) to be included without making any assumptions about error structure. For each main net/codend mesh combination, four tows were sampled from the original replicates with replacement, as were individual fish lengths from both the codend and codend cover subcatches of these tows. When length frequencies were subsampled, numbers at length were scaled up to the estimated total number caught in that subcatch. For both the codend and codend cover, the four bootstrapped tow length frequencies were then combined and selection curves fitted. This procedure was repeated 500 times, from which average and 95 percent confidence ranges for selectivity at length were calculated. Estimates of the length at which 50% retention occurs (L_{50}) and the length range between which 75% and 25% selection occurred (SR = $L_{75} - L_{25}$) were calculated as follows:

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

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

These bootstrap results were displayed on plots of L_{50} against the selection range to facilitate appreciation of the scatter and any correlation between estimated parameters.

3.3.1.3 Estimation of relative catch rates of 80 and 100 mm meshes in the net

Relative selectivity (at length) of the 80 and 100 mm main net meshes was explored using an alternate tow approach (Wilemann et al. 1996). As a common codend cover mesh (12 mm) was used on all tows, differences between the total catches (all three subcatches combined) can be ascribed solely to the selective properties of the main net mesh. This assumes that the configuration and spread of both nets was the same during fishing.

Preliminary analysis, using the alternate tow method, suggested that there was no change in the relative selectivity of the two main net mesh sizes with increasing fish length. As the more abundant fish species were small relative to the main net mesh sizes used, this may not be surprising. The length frequency distributions of catches caught using the 80 and 100 mm nets (Figures 13–18) also suggested no significant differences in selectivity at length for these species. Larger species such as hoki, ling, and frostfish, whose retention may have been influenced by the size of the main net mesh, were caught in insufficient numbers to estimate selectivity at length reliably. The alternate tow approach is usually based on two or more mesh types of substantially different sizes. The size of the smaller mesh should, ideally, be considerably more selective for smaller fish than the larger mesh. It is the contrast in how two or more mesh sizes select fish over a broad size range that permits an estimate of the selective properties of the larger mesh to be obtained. As there was no apparent difference between the selective properties of the 80 and 100 mm main net meshes for any of the more abundant species, estimation of how these meshes selected different size fish was not possible.

Differences in selectivity across all lengths were investigated by comparing catch rates of predominant species (as caught by all components of the net including the codend cover). Although the length frequency distributions of fish caught in tows using 80 and 100 mm main net meshes were broadly similar for most species, differences in overall catch rates might occur if fish respond differently to the two meshes. Catch rates from the 12 replicate tows using 80 and 100 mm main net meshes were first compared using t-tests (not α-corrected for multiple tests). Because preliminary analysis suggested that the 80 mm mesh caught more scampi than the 100 mm mesh, the catch rate for each bycatch species was expressed in terms of the weight of bycatch per kilogram of scampi caught. Average bycatch rates were calculated from the 12 replicate tows using the ratio of the mean catch rates of scampi to the mean catch rate of each of key bycatch species, which has been found to be an unbiased estimator of bycatch rates (Ye 2002). Ratios of 80 mm catch (per kilogram of scampi) to 100 mm catch (per kilogram of scampi) were then calculated for each species. Values less than 1.0 indicate that a greater weight of that species is caught per kilogram of target species when the 100 mm mesh was used, and vice versa. Variability (95% confidence intervals) around these ratios was derived using a bootstrap procedure, in which catches from the 12 replicate tows (for each mesh), were sampled 500 times with replacement for both scampi and the bycatch species, with ratios calculated as above.

3.3.2 Results

3.3.2.1 Codend selectivity

Only six species were consistently found in codend and codend cover subcatches in substantial numbers: scampi, silver roughy, javelinfish, "other rattails" (i.e., not including javelinfish), sea perch, and capro dory (Table 2). Some species were caught in appreciable numbers in occasional tows (e.g., Lucifer's dogfish and red cod), but not consistently enough to warrant further analysis (Table 3, Appendix 2). Some larger species (e.g., hoki) were fully retained by the codend and were never found in the cover (Table 4). For most species, however, the numbers caught were considered too low to reliably estimate selectivity at length (Appendix 2). For each of the six species examined there were usually no marked differences between the combined length frequency distributions of fish retained in the codend and its cover for each of the six mesh combinations tested (Figures 13–18). The results derived from each mesh type combination are, therefore, directly comparable, because factors such as the area trawled, depth, tow length, and tow speed were standardised.

Not surprisingly, more small fish were retained by codends of finer meshes; the 65 mm codend allowed many more small fish to pass through to the cover than did the 30 and 55 mm codends. Almost all abundant size classes of scampi were fully retained by the 30 and 55 mm codends, whereas the 65 mm codend allowed some animals smaller than 35 mm OCL through to the cover. All three codend meshes tested retained some scampi smaller than 25 mm OCL. These animals are probably immature (Cryer & Oliver 2001) and their capture is unlikely to be biologically or commercially desirable. Other studies, however, suggest that scampi of this size emerge from their burrows only rarely (Cryer et al. 2001), suggesting they are never likely to be a large component of the catch, whatever mesh size is used. Some small javelinfish and rattails were allowed through to the cover by all codend meshes. Silver roughy, sea perch, and capro dories were fully retained by the 30 and 55 mm codends, although some smaller fish were allowed through to the cover by the 65 mm codend. Some correlation is evident between bootstrap estimates of L_{50} and selection range for most of the mesh combinations tested (Appendix 3). The distribution of these bootstrap estimates suggests that analytical confidence intervals for these parameters may give misleading results.

Table 2: Number of measurements of scampi and the ten most common bycatch species in the covered codend experiment (in descending order of total number measured). Only the first six species listed were analysed in full, based on a criterion of at least 100 measurements in each mesh size combination.

		Mesh sizes (codend/main)					
Species	Code	30/100	30/80	55/100	55/80	65/100	65/80
Silver roughy	SRH	833	4 651	4 261	18 812	866	9 957
Javelinfish	JAV	1 073	1 747	5 843	5 152	1 300	1 998
Other rattails	RAT	891	1 013	6 797	2 028	598	1 474
Scampi	SCI	915	1 142	1 276	4 034	672	2 464
Sea perch	SPE	775	1 734	1 259	1 998	1 084	1 900
Capro dory	CDO	289	796	437	696	350	477
Lucifer's dogfish	ETL	99	265	103	208	35	74
Red cod	RCO	42	125	82	138	26	75
Deepsea flathead	FHD	64	102	26	88	33	105
Silverside	SSI	34	49	51	58	64	34
Ling	LIN	15	11	8	32	9	12
Total (of above)	–	5 030	11 635	20 143	33 244	5 037	18 570

Table 3: Mean numbers and weight (kg) of scampi and the five other bycatch species for which selectivity was estimated. Numbers and weights are given for the three subcatches for each combination of main net and codend mesh.

	Mesh sizes (codend /	Codend		Cover		Wings	
Species	main, mm stretched)	N	kg	N	kg	N	kg
SCI	30/80	1 059	68.1	10	0.3	73	4.1
(Scampi)	30/100	814	51.8	8	0.3	93	5.1
	55/80	3 837	211.9	13	0.3	184	8.2
	55/100	1 177	85.1	42	0.6	57	4.1
	65/80	2 235	138.5	105	2.2	124	6.3
	65/100	555	35.8	57	1.3	60	3.5
SRH	30/80	4525	128.0	51	0.5	75	2.2
(Silver roughy)	30/100	786	66.8	45	0.5	2	0.2
	55/80	18 533	303.7	194	4.1	85	2.9
	55/100	3 841	178.0	417	6.9	3	0.3
	65/80	7 972	316.5	1 894	49.8	91	3.6
	65/100	298	10.2	567	8.8	1	0.1
JAV	30/80	1 514	89.3	170	1.8	63	9.0
(Javelin fish)	30/100	980	84.6	89	1.1	4	0.9
	55/80	4 850	170.0	229	5.8	73	9.0
	55/100	5 209	178.8	626	10.6	8	1.5
	65/80	1 307	118.5	613	24.8	78	9.0
	65/100	211	22.3	1 083	21.0	6	1.6
RAT	30/80	855	30.5	158	1.9	–	–
(Rattails)	30/100	777	47.5	113	1.7	1	0.3
	55/80	1 383	44.6	635	9.1	10	0.4
	55/100	6 111	45.8	685	13.3	1	0.4
	65/80	641	24.8	832	17.3	1	0.2
	65/100	258	31.9	339	10.5	1	0.3
SPE	30/80	1 635	101.6	85	1.7	14	1.1
(Sea perch)	30/100	702	49.1	73	1.3	–	–
	55/80	1 713	103.8	277	6.1	8	0.6
	55/100	1 099	85.8	160	4.3	–	–
	65/80	808	53.2	1 087	30.8	5	0.4
	65/100	511	39.7	573	22.2	–	–
CDO	30/80	763	11.2	4	0.4	29	0.6
(Capro dory)	30/100	280	5.1	2	0.2	7	0.4
	55/80	640	11.0	29	0.4	27	0.5
	55/100	405	7.7	30	0.5	2	0.2
	65/80	299	3.3	161	3.1	17	0.5
	65/100	158	2.8	187	3.3	5	0.2

Table 4: Mean numbers and weight (kg) of abundant bycatch species for which selectivity was not estimated. Numbers and weights are given for the three subcatches for each combination of main net and codend mesh.

Species	Mesh sizes (codend / main, mm stretched)	Codend		Cover		Wings	
		N	kg	N	kg	N	kg
HOK	30/80	174	286.0	–	–	1	2.0
(Hoki)	30/100	150	306.8	–	–	21	31.3
	55/80	181	269.7	–	–	–	–
	55/100	176	336.8	–	–	17	22.7
	65/80	143	227.4	–	–	–	–
	65/100	88	172.1	–	–	3	7.4
RCO	30/80	116	27.6	4	0.1	1	0.2
(Red cod)	30/100	42	16.8	–	–	–	–
	55/80	78	15.4	15	0.5	–	–
	55/100	65	20.0	11	0.5	–	–
	65/80	42	11.5	33	1.5	–	–
	65/100	20	8.3	6	0.6	–	–
FRO	30/80	7	0.1	11	0.1	3	0.1
(Frostfish)	30/100	2	1.8	–	–	–	0.1
	55/80	8	15.7	–	–	–	–
	55/100	31	23.4	8	0.2	7	0.1
	65/80	204	19.4	110	2.0	54	1.4
	65/100	4	4.7	–	–	–	1.7
APG	30/80	12	0.3	17	0.4	–	–
(Cardinalfish)	30/100	11	0.3	5	0.2	–	–
	55/80	32	0.5	30	0.6	–	–
	55/100	2	0.1	2	0.2	–	–
	65/80	–	2.0	23	0.4	–	–
	65/100	–	–	7	0.3	–	–
LIN	30/80	9	28.2	2	0.2	–	–
(Ling)	30/100	15	31.8	–	0.1	–	–
	55/80	27	67.9	5	0.2	–	–
	55/100	7	15.4	1	0.1	–	–
	65/80	10	14.7	2	0.2	–	–
	65/100	8	14.1	1	0.1	–	–
SKI	30/80	3	14.1	–	–	–	–
(Gemfish)	30/100	6	19.7	–	–	–	–
	55/80	9	34.9	1	0.1	–	–
	55/100	8	36.6	–	–	–	–
	65/80	4	11.5	3	0.1	1	0.6
	65/100	4	12.0	2	0.2	–	–

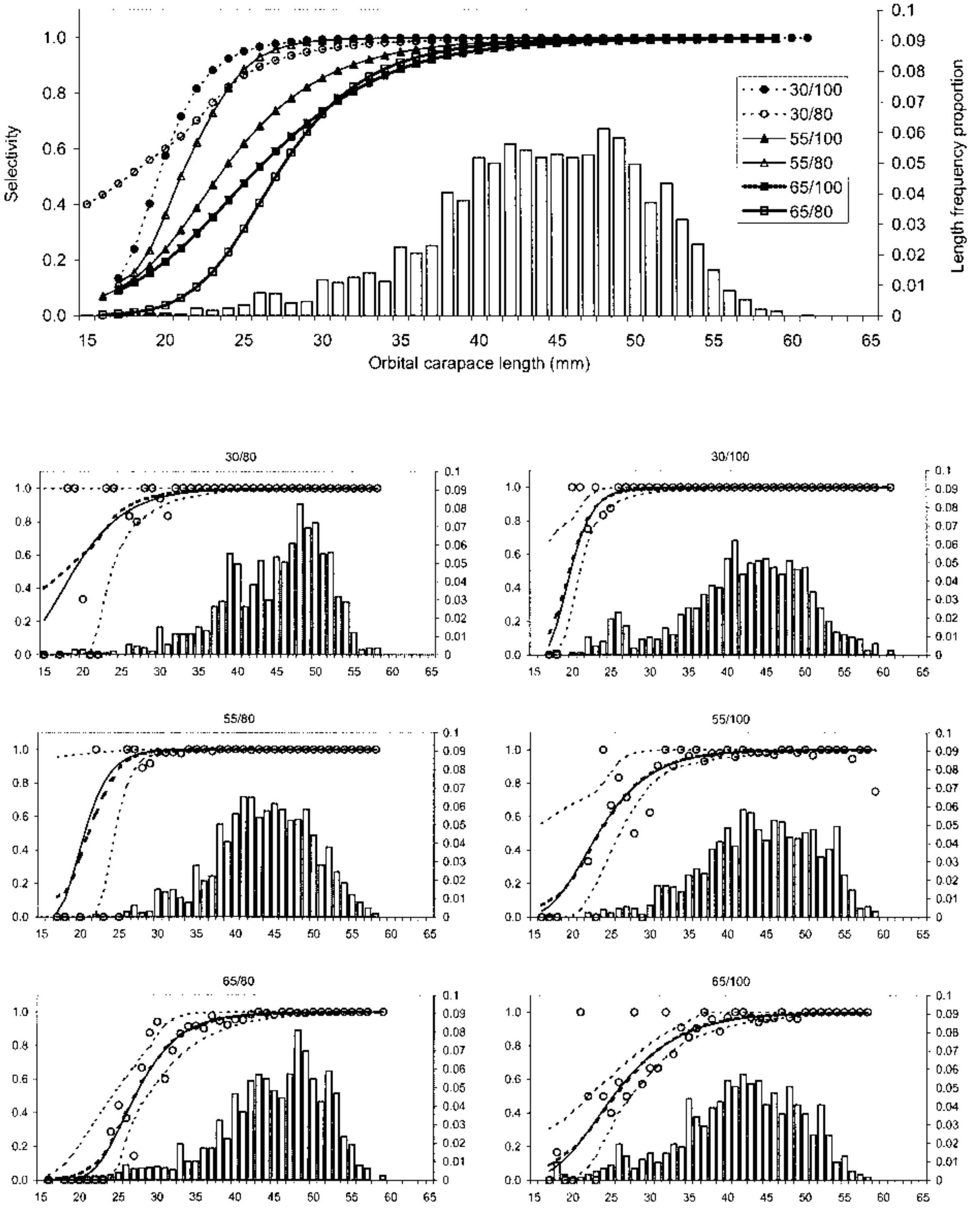


Figure 13: Estimated codend selectivity of Florida Flyer trawl gear for scampi. The top panel shows the overall length frequency distribution and estimated codend selectivity for six mesh combinations used (specified as codend/main net mesh in the legend), and the smaller panels show each curve plotted separately with the observed data points and 95% confidence bounds for the curve from a bootstrap procedure. The length frequency distributions of animals used to fit each curve are superimposed as histograms and the observed fraction of each length class retained in the codend is denoted by circles.

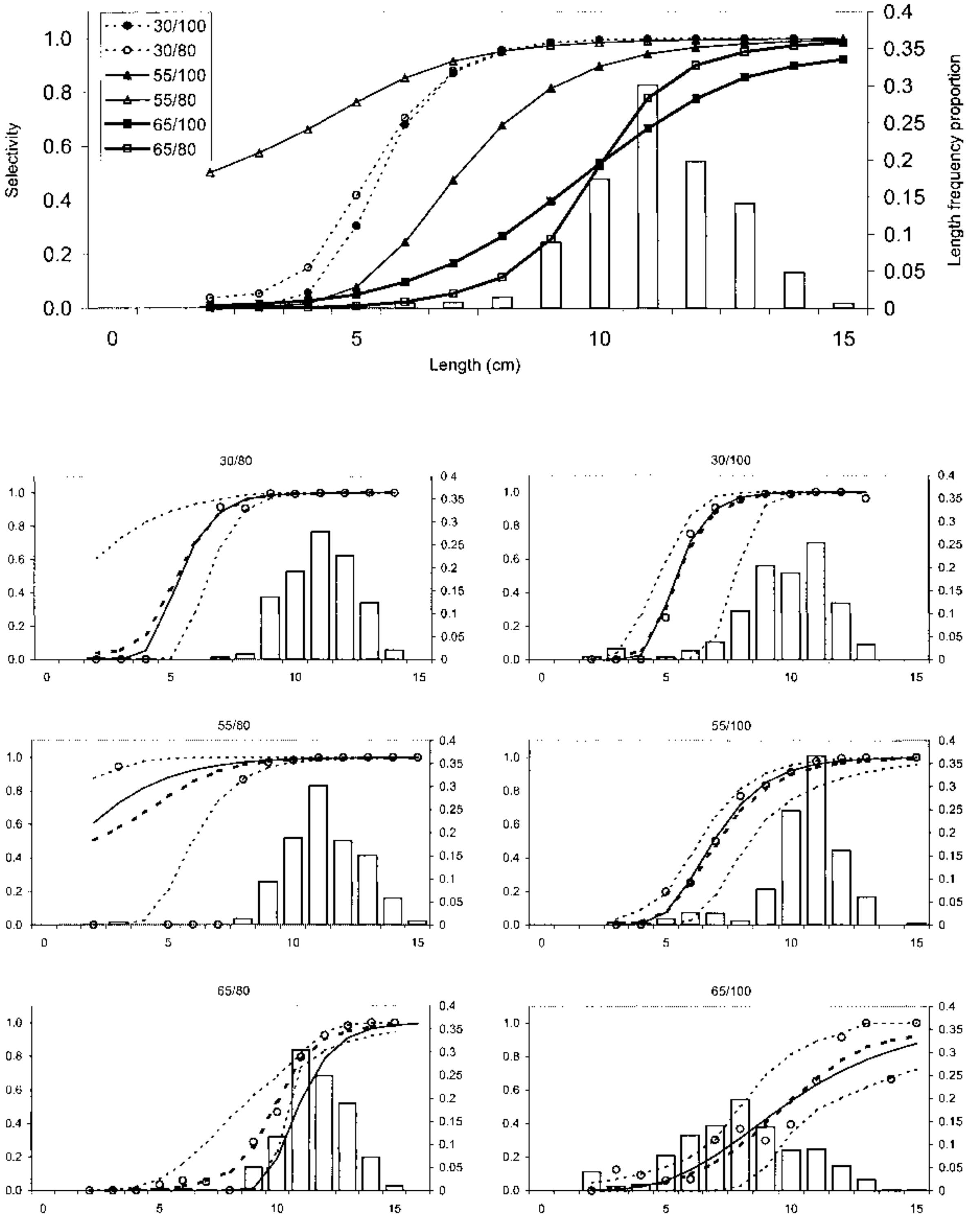


Figure 14: Estimated codend selectivity of Florida Flyer trawl gear for silver roughy. The top panel shows the overall length frequency distribution and estimated codend selectivity for six mesh combinations used (specified as codend/main net mesh in the legend), and the smaller panels show each curve plotted separately with the observed data points and 95% confidence bounds for the curve from a bootstrap procedure. The length frequency distributions of animals used to fit each curve are superimposed as histograms and the observed fraction of each length class retained in the codend is denoted by circles.

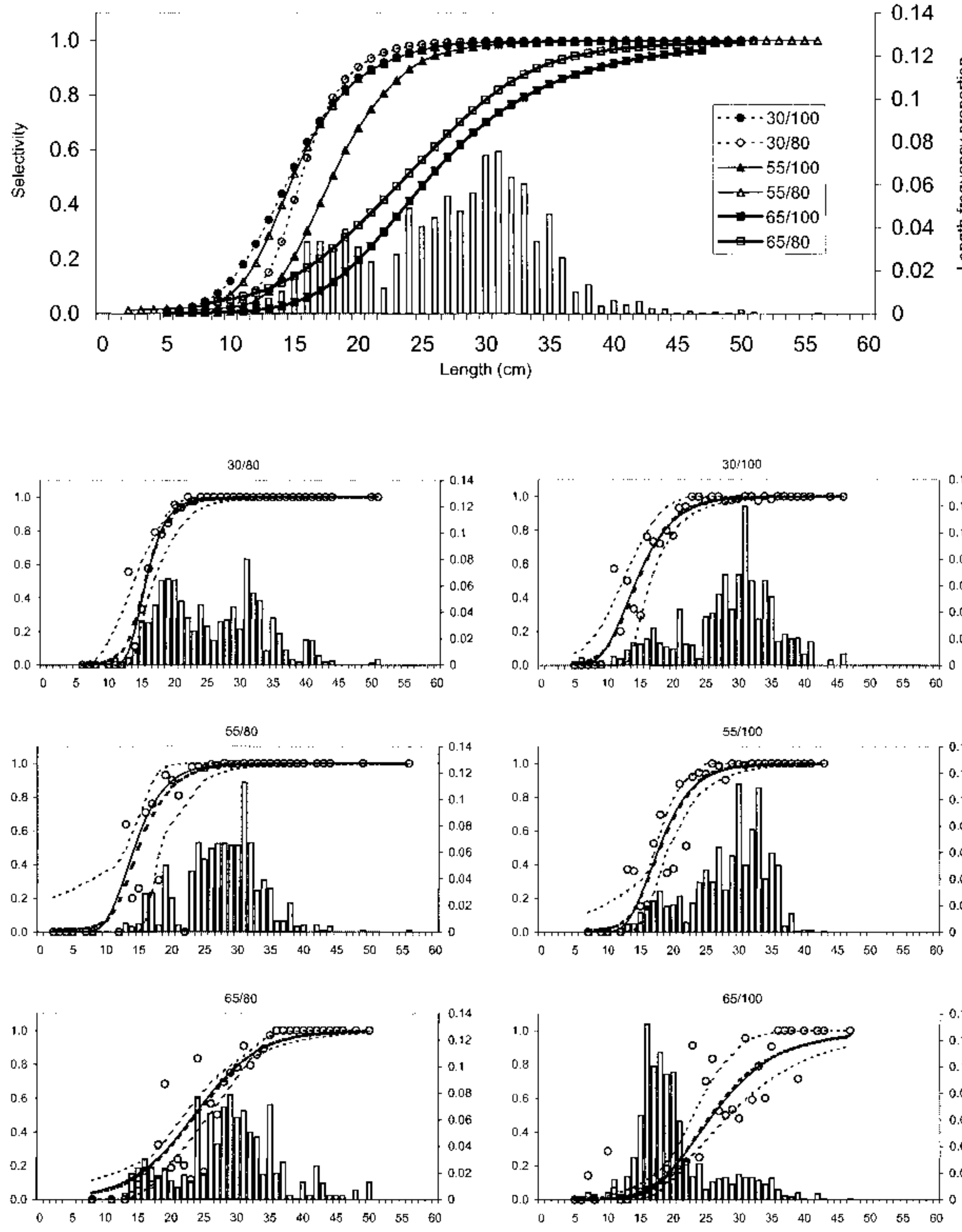


Figure 15: Estimated codend selectivity of Florida Flyer trawl gear for javelinfish. The top panel shows the overall length frequency distribution and estimated codend selectivity for six mesh combinations used (specified as codend/main net mesh in the legend), and the smaller panels show each curve plotted separately with the observed data points and 95% confidence bounds for the curve from a bootstrap procedure. The length frequency distributions of animals used to fit each curve are superimposed as histograms and the observed fraction of each length class retained in the codend is denoted by circles.

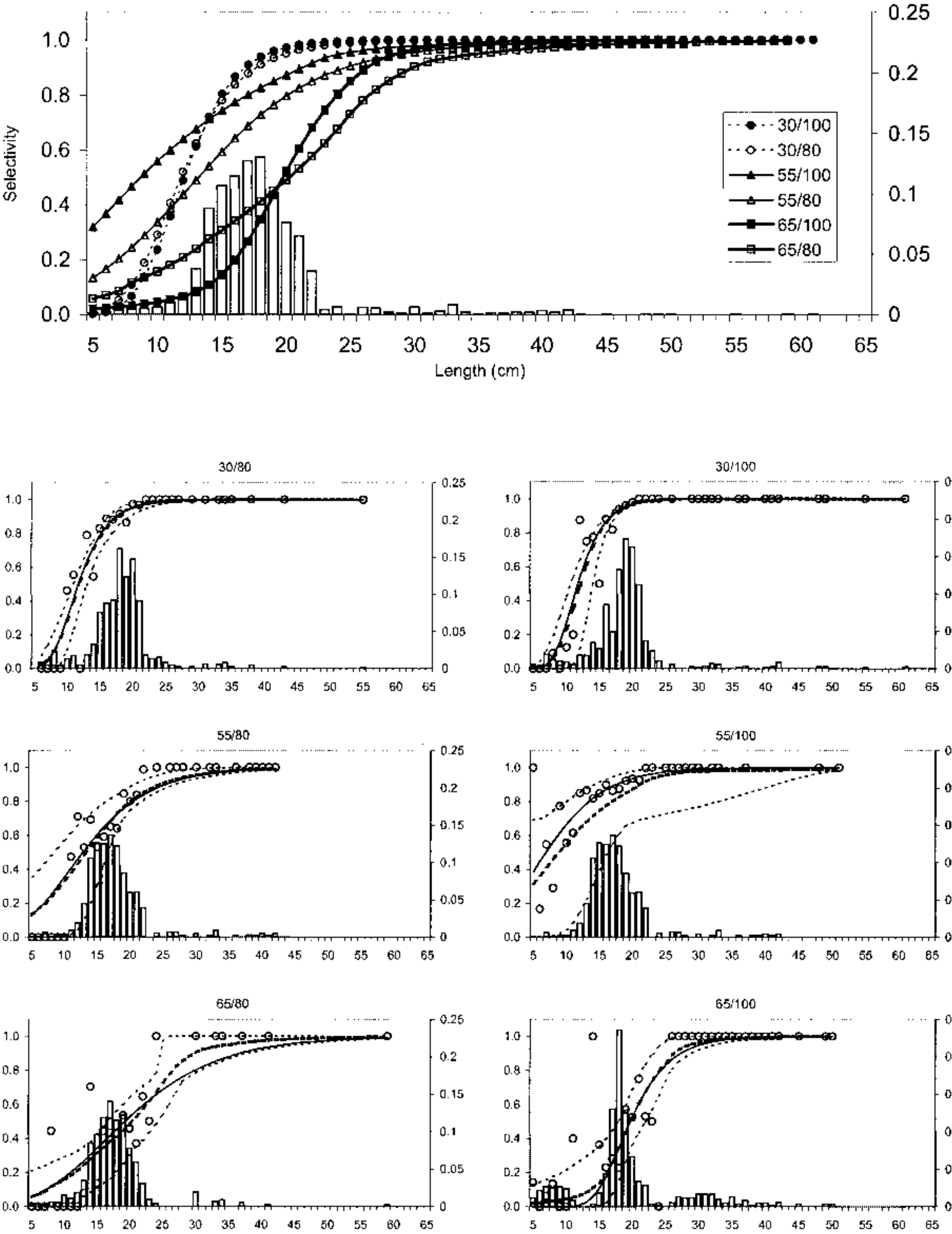


Figure 16: Estimated codend selectivity of Florida Flyer trawl gear for rattails. The top panel shows the overall length frequency distribution and estimated codend selectivity for six mesh combinations used (specified as codend/main net mesh in the legend), and the smaller panels show each curve plotted separately with the observed data points and 95% confidence bounds for the curve from a bootstrap procedure. The length frequency distributions of animals used to fit each curve are superimposed as histograms and the observed fraction of each length class retained in the codend is denoted by circles.

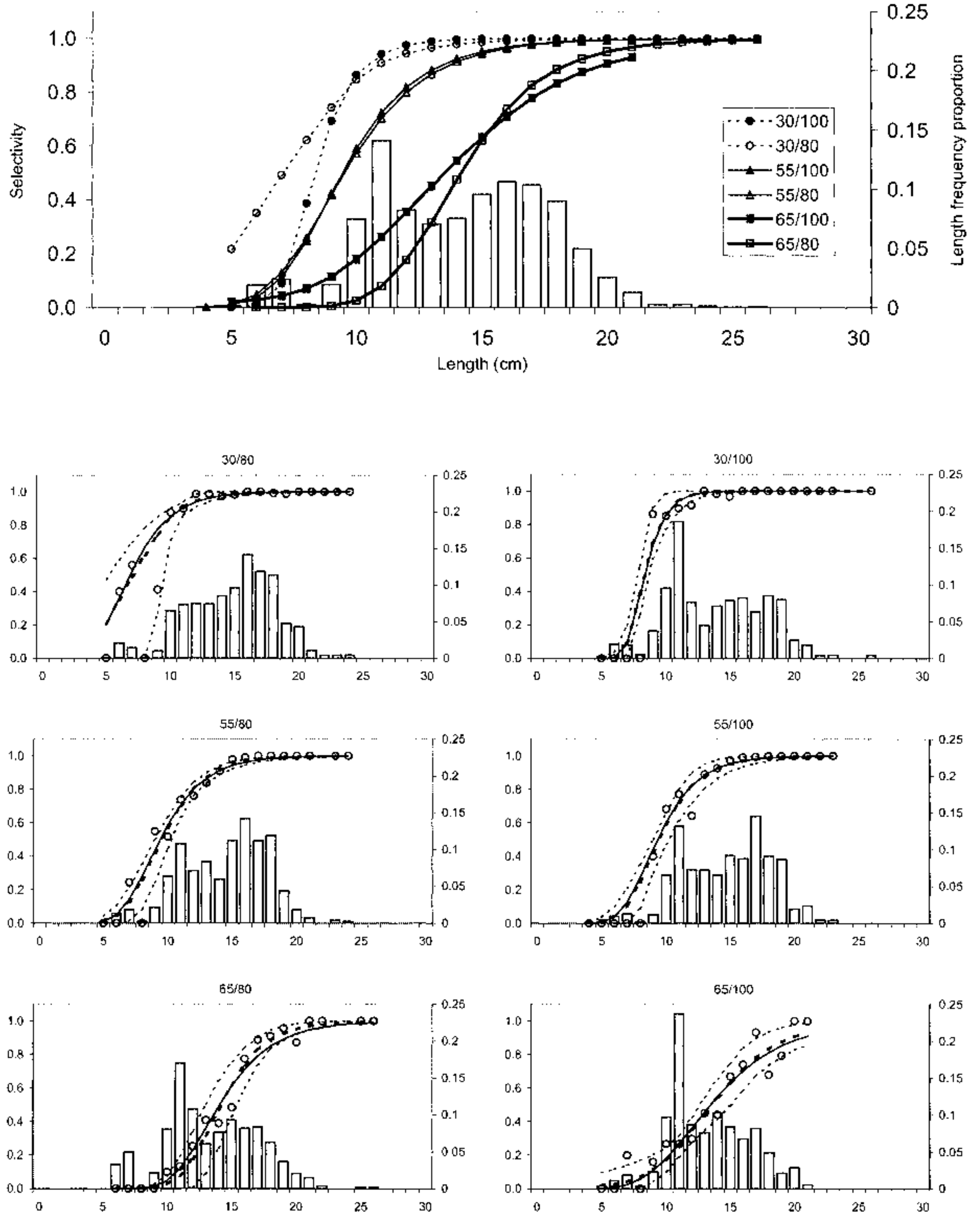


Figure 17: Estimated codend selectivity of Florida Flyer trawl gear for sea perch. The top panel shows the overall length frequency distribution and estimated codend selectivity for six mesh combinations used (specified as codend/main net mesh in the legend), and the smaller panels show each curve plotted separately with the observed data points and 95% confidence bounds for the curve from a bootstrap procedure. The length frequency distributions of animals used to fit each curve are superimposed as histograms and the observed fraction of each length class retained in the codend is denoted by circles.

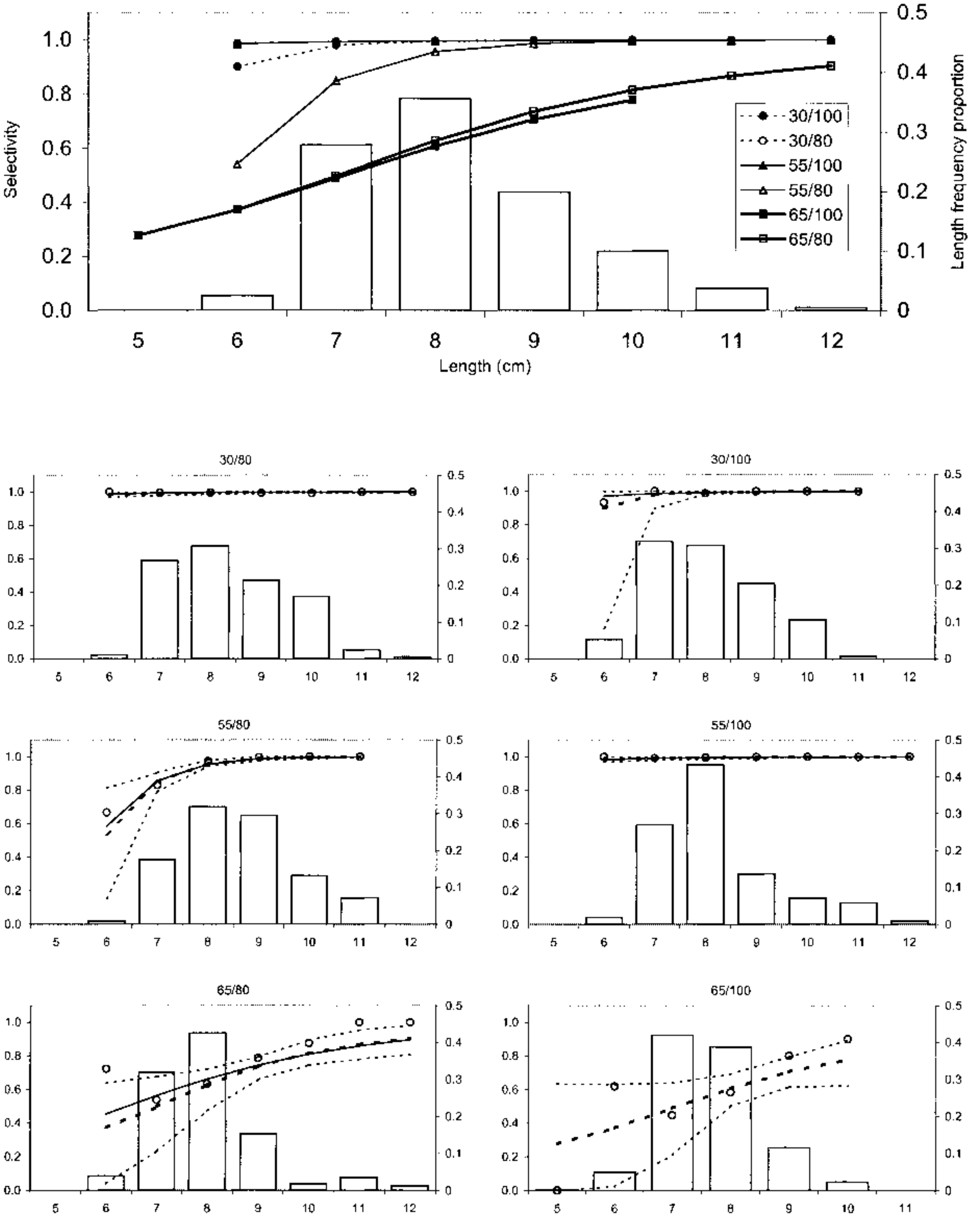


Figure 18: Estimated codend selectivity of Florida Flyer trawl gear for capro dories. The top panel shows the overall length frequency distribution and estimated codend selectivity for six mesh combinations used (specified as codend/main net mesh in the legend), and the smaller panels show each curve plotted separately with the observed data points and 95% confidence bounds for the curve from a bootstrap procedure. The length frequency distributions of animals used to fit each curve are superimposed as histograms and the observed fraction of each length class retained in the codend is denoted by circles.

3.3.2.2 Relative catch rates of 80 and 100 mm meshes in the main net

For some species, average catch rates using the two mesh sizes were markedly different (Figure 19); significantly more scampi (t = 2.69, p = 0.021) and sea perch (t = 3.24, 9 = 0.008) were caught using 80 mm mesh than using 100 mm mesh, although the length frequency distributions were similar. As most of the catch of these two species was in the codend or codend cover, it appears that the larger meshes in the body and the wings may act as a poorly selective funnel.

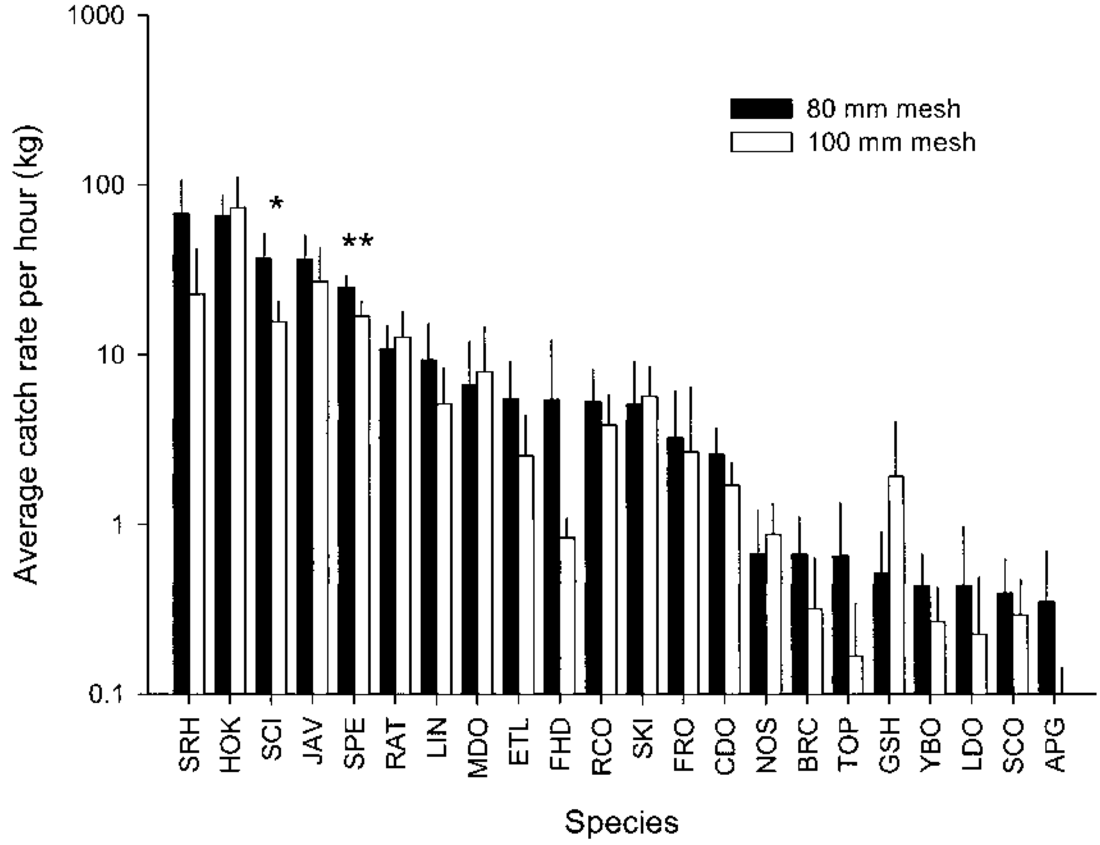


Figure 19: Mean catch rate per hour trawled for scampi (SCI) and the 20 most common bycatch species (by weight) using Florida Flyer trawls with 80 or 100 mm main net mesh in the body and wings. Asterisks denote statistically significant differences from paired sample t-tests (*, $p < 0.05$; **, $p < 0.01$). Species codes are defined in Appendix 2.

Although the 100 mm mesh trawl usually caught less bycatch per tow, it caught more bycatch per kilogram of scampi (i.e., the catch of scampi declined more than the bycatch of most fish species when the coarser mesh was used) (Figure 20). Thus, under a regime of limited catch (rather than limited effort), less trawling effort would be required to take an annual catch allocation of scampi using 80 mm mesh than with 100 mm mesh, and less total bycatch would be taken using the finer mesh. Further, reduced trawling effort using 80 mm mesh should lead to fewer "unobserved" effects such as habitat modification and damage to organisms not retained in the net.

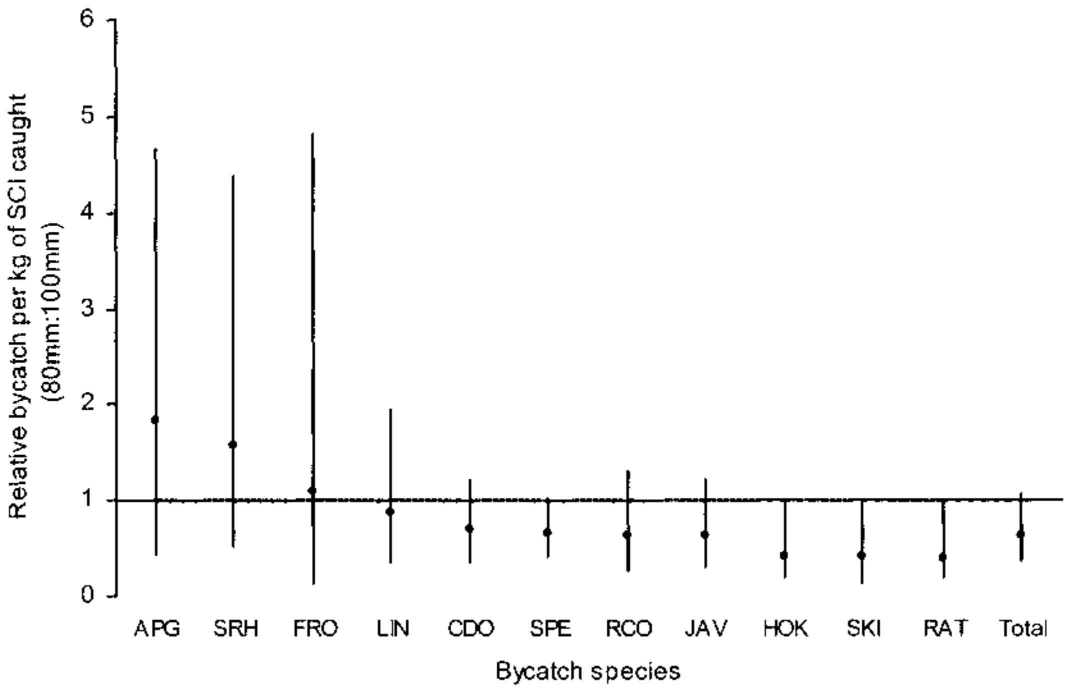


Figure 20: Bycatch rates (per unit of scampi catch) of the 80 mm trawl relative to the 100 mm trawl (with 95% confidence ranges from a bootstrap procedure) for the 11 most common bycatch species and for total catch of all bycatch species. The index for each species is calculated as the weight caught per kilogram of scampi in the 80 mm trawl divided by the weight caught per kilogram of scampi in the 100 mm trawl. Thus, values under 1 indicate an increased bycatch of that species when 100 mm mesh trawls are used to catch a fixed annual allocation of scampi, and vice versa. Species codes are defined in Appendix 2.

3.4 Discussions with the fishing industry

Discussions were held with two of the most experienced participants in the New Zealand scampi fishing industry (Neil Penwarden, Barine Developments, and Vaughan Wilkinson, Simunovich Fisheries, now Sanford Ltd.), about their experiences in trying to reduce bycatch. Both participants have conducted bycatch reduction gear trials of their own volition, although with the exception of one study undertaken in collaboration with the former MAF Fisheries in 1992, no data were made available for detailed analysis. Nordmøre grids were trialled by both participants, but not adopted because of concerns about loss of scampi, crew safety, and difficulties experienced during deployment and retrieval. A disc-shaped grid was also trialled and considered unsatisfactory. The most widely adopted approach to reducing bycatch by the fishing industry has been to increase mesh sizes in both the body and codend of the net. Since 1992, the minimum legal mesh sizes have been 55 mm in the codend, and 80 mm in the body of the nets. Both fishing companies have, however, routinely constructed net bodies out of 100 mm mesh since the early to mid 1990s, and have experimented with mesh sizes greater than 55 mm in the codend. A variety of twine sizes have been trialled on an informal basis. Another approach, which has been adopted operationally, has been to modify nets so that the headline does not overhang the groundrope. Larger meshes in top panels have also been tested, but not universally adopted.

There is no uniformity in the design of fishing gear used by different fishing companies. Most vessels tow triple trawl rigs, and the remainder tow double-rigged nets. Concerns were expressed about the recent requirement to land sea perch following the species' introduction into the quota management system. Most of the sea perch catch is of unmarketable size, and any means of reducing this bycatch would be welcomed. Marketable bycatch species make up only a small proportion of the value of a landed catch. One fisher suggested that gear modifications which excluded these marketable bycatch species would be acceptable if scampi catch rates were not adversely affected.

4. FUTURE WORK

4.1 General considerations

One objective of this study was to recommend performance standards, and the design of field gear trials, to achieve reductions of non-target fish catch in the New Zealand scampi fishery. However, the development of any method of reducing bycatch involves a set of trade-offs among ecological consequence, economic efficiency, and practicality. In considering different approaches, it is crucial to have a clear understanding of the management objectives for the fishery and its bycatch, and that these be stated explicitly. This is not a step that can or should be undertaken by a research provider and should, ideally, involve managers and all stakeholders in the fishery. Once management objectives are clearly defined, appropriate bycatch reduction approaches can be investigated, and feasible performance standards set. Regardless of the approach taken, however, there are general principles that should be considered. Principles relating to trawl fisheries generally were discussed by Booth et al. (2002), but further consideration of the scampi fisheries is required because of the unique construction of the fishing gear and the nature and extent of the bycatch.

Most bycatch from New Zealand scampi fisheries is of small finfish with little or no commercial value. Overseas studies, however, especially those relating to European *Nephrops norvegicus* fisheries, have tended to focus on the reduction of the bycatch and discards of juveniles of larger species that are commercially fished.

Incidental impacts of scampi fishing resulting from the physical contact of trawl gears on the seafloor are not discussed in any detail in this report, but have been shown to be significant on the Bay of Plenty continental slope (Cryer et al. 2002). From a study of the effects of otter trawling on the "*Nephrops* community" in the northwest Irish Sea, Tuck et al. (1998) concluded that disturbance had a greater impact than direct removal on benthic communities. Similarly, Linnane et al. (2000) suggested that, for most invertebrate species, mortality of animals caught in trawl nets was only a small fraction of the total mortality imposed by trawl gear. Thus, the environmental impact of the scampi fishery could, paradoxically, be exacerbated by introducing methods of reducing bycatch that decrease scampi catch rate (and concomitantly increases fishing effort). Linnane et al. (2000) also reported that recent studies into gear selectivity in Irish waters have tended to concentrate on reducing non-target and juvenile fish bycatch, but no attempts have been made to reduce the benthic bycatch or the potential damage of demersal fishing gears on benthic communities. Our literature search suggests that this is common in many overseas fisheries, despite a growing recognition of the impacts of trawling on benthic systems (Dayton et al. 1995, Thrush et al. 1998, Hall 1999, Cryer et al. 2002).

Because of differences in species behaviour, morphology, swimming ability, growth rates, and community composition, bycatch reduction technology must be tuned to a fishery to ensure that its performance is optimal given the management objectives. Robins & McGilvray (1999) suggested that the location of the trial and the associated quantity and composition of the bycatch was probably the most influential factor determining the efficiency of a particular device in a particular location. Fishing gears used on New Zealand scampi grounds appear to be based upon the adoption of overseas technology, which has been adapted ad hoc to New Zealand conditions. A wide variety of approaches is available, some of which could be used in combination. In order to determine which of these is suited to the New Zealand scampi fishery, it is necessary to have some understanding of the following:

- The species and size composition of the bycatch and how this might vary by location, depth, season, and the construction of the gear currently in use.
- The behaviour of the predominant species when encountering fishing gear.

- The commercial needs of fishers who may (or may not) wish to retain some species when targeting scampi.
- The wide variety of practical considerations in deploying bycatch reduction gear routinely during commercial fishing.

We will consider each of these in turn.

4.2 Species composition

Available data suggests that bycatch species composition differs markedly among QMAs. The spatial and temporal resolution of these data in some areas may be insufficient to determine management issues, and further dedicated work may be required in this area. Ministry of Fisheries observers have collected extensive data on scampi trawl bycatch composition, but the focus of this programme has been on measuring the scampi catch and QMS finfish species. Information on the bycatch of non-commercial finfish species and invertebrates is relatively poor, and has been recorded inconsistently (e.g., Cryer et al. 1999, Cryer & Coburn 2000, Hartill & Cryer 2000). This is not surprising given the wide variety of fish and invertebrates found in the bycatch of scampi trawls. Some estimates of discard rates from the scampi fishery are available (Anderson 2004), but these are based on observer data and are, therefore, only indicative. More detailed data are available from research trawl surveys, although these are based on finer mesh sizes (body mesh 80 mm, codend mesh 35 mm) than those used in the commercial fishery, and restricted to certain core grounds in QMAs 1, 2, and 3.

Despite the acknowledged problems with the data from scientific observers, Cryer (2000) examined patterns in the bycatch of scampi trawl fisheries on the Chatham Rise (QMAs 3 and 4) and close to the Auckland Islands (QMAs 6A and 6B). He found significant trends in the amount of bycatch, both in absolute terms and in relation to the catch of scampi. General linear modelling suggested that the absolute weight of finfish bycatch was lower during autumn and winter, but this was offset by the lower catch rates of scampi at that time of year. When expressed relative to the catch of scampi, least bycatch was taken in late summer on the Chatham Rise and in spring off the Auckland Islands. There were distinct spatial trends and trends with depth in both areas suggesting that the precise location of fishing can have a profound effect on the amount and species composition of the bycatch. For example, the finfish bycatch of trawling for scampi on the Mernoo Bank on the western Chatham Rise averaged more than 90% of the total catch, compared with an overall average for QMAs 3 and 4 of less than 85%. The trend in QMA 6 is similarly marked, and the proportion of bycatch there increases from about 65% to about 75% over a distance of about 75 nautical miles. Maintaining a bycatch of 65% of total catch instead of 75% for a 300 t fishery (scampi catch limits for QMAs 6A and 6B combined) would reduce the (hypothetical) absolute weight of bycatch from about 900 t to about 550 t, a "saving" of 350 t. Similarly, maintaining a bycatch of 85% of total catch instead of 95% for the 310 t Chatham Rise fishery (catch limits for QMAs 3 and 4 combined) would reduce the (hypothetical) absolute weight of bycatch from almost 6000 t to less than 1800 t, a "saving" of more than 4000 t. Cryer (2000) found a trend of similar magnitude with depth (more bycatch per unit weight of scampi in shallower tows) in QMA 6 but not in QMAs 3 and 4.

None of these numbers is an accurate estimate of the actual tonnage of bycatch taken in a particular area, but they illustrate that relatively simple measures such as shifting the timing, location, or depth of fishing can have profound effects on the composition and amount of bycatch. These "natural" methods should be considered alongside technical methods; it may be that timing and locating trawling effort to minimise bycatch in relation to scampi catch could match the gains brought about by the introduction of bycatch reduction devices.

4.3 The importance of behavioural responses

There are many possible approaches to reducing bycatch in scampi trawl fisheries, although overseas researchers repeatedly state that bycatch technology should be tailored to each fishery if target catch rates are to be maintained. A first step to identifying the most promising approaches would be understanding how scampi and non-target species behave when encountering trawl gear. Studies of behaviour have provided the basis for many strategies to reduce bycatch in many fisheries (Main & Sangster 1985, Engås & West 1995, Wardle 1995, Wileman 1995, Armstrong et al. 1998.) To some extent, the likely behaviour of *Metanephrops* can be inferred from overseas observations of how *Nephrops* reacted when trawl gear was encountered. Diver observations have shown that *Nephrops* briefly swam as high as 75 cm off the bottom during trawling operations and horizontal separator panels were rigged accordingly (Main & Sangster 1985). Observations in these studies suggested that after an initial fright response, *Nephrops* reacts to towed gears in a comparatively passive manner. No *Nephrops* were herded inwards by the sweeps or bridles during 4 hours of observation. During one 6-minute observation period, 27 individuals were seen to swim off the seabed over the ground rope and to collide with the lower wing meshes (70 mm) before rolling and tumbling into the net mouth. Once in the net, *Nephrops* rolled and tumbled along the net belly towards the codend and did not appear to attempt to escape.

Some understanding of the behaviour of non-target finfish species would also be desirable. To date, all studies of finfish behaviour when encountered by trawl gears have been conducted overseas. Hemmings (1973) demonstrated clear differences in the behavior of finfish species encountering trawl gears inferred from diver observations. Flatfish exhausted at the mouth of the net eventually rose above the ground rope and fell back into the net. Haddock swam in front of, and above, the headline, and were only partially retained by the closing net, while saithe dived under the ground rope when possible. Unfortunately, for New Zealand fisheries generally, such an understanding of avoidance behaviour is lacking, and it is, therefore, not possible to develop bycatch reduction or target species retention technology based on these behaviours. Behaviour can be observed or inferred using divers, low light video cameras, still cameras with flashes, or by small mesh horizontal separator panels placed at different heights and distances back from the ground rope. Given the depths fished, only some of these options are feasible.

4.4 Experimental design

When evaluating a gear type, fishing practices should be based upon those in current use by the fishery. Where possible, methods should be standardised, to reduce between-tow variability and ensure that catch differences are due to gear performance rather than extraneous influences. As behaviour is likely to change diurnally, the timing of tows should be standardised to minimise variability in catchability as seen in commercial CPUE data (Cryer et al. 1998). Such patterns are also likely to exist for non-target species, including finfish. Engås & Soldal (1992) found day-night shifts in the ratio of cod to haddock in the catch in depths between 270 and 340 m. Tow speeds, tow durations, depths fished, areas fished and configurations of net components should also be standardised to maintain comparability. As the weight of the total catch has a dynamic effect on gear configuration and, hence, its selectivity (Briggs 1986), tow length should ideally be based on industry practice. Given the number of tows required to assess the variability of a gear type however, this may not be economic, as commercial tows average at least 5 hours in duration in most areas (Cryer et al. 1998).

There are two main methods of assessing the efficiency of bycatch reduction gear: cover methods and paired-gear methods. Cover methods involve the direct measurement of fish escaping a gear by fitting fine mesh covers over the gear, thus retaining the escapees. Paired gear methods – alternate tow, parallel haul, twin trawl, and trouser trawl methods – involve the indirect comparison of two or more gear types, from which relative selectivity is inferred. Direct estimates of selectivity derived from cover experiments have the very desirable property that each haul results in weights (retained and not retained) and selectivity curves (when sufficient numbers are caught) for all species encountered. Assessment of between-tow variability is also much more tractable using this method, because species specific catch weights and selectivity curves from each tow can be directly compared. Covers must be designed carefully, however, to avoid masking and changes to hydrodynamic flow within the net. Some researchers have successfully used hoops or kites to reduce these effects (Madsen et al. 2001). The disadvantage of direct methods is that they allow measurement of the selectivity of only those parts of the net that are covered, usually the codend. The overall selectivity of a trawl net is the aggregate effect of all components, and catch rates of different species are likely to be influenced differently by the size and configuration of meshes in the main net and the codend.

Paired gear methods are based on the indirect comparison of catches from two or more gear types. One gear type is usually constructed out of a small mesh, which retains all of the fish falling into the trawl, although the increased catch weight may change the fishing characteristics of the trawl gear. It is essential in these studies that all gears are exactly identical except for the component being tested. With the alternate tow approach, at least one tow of each gear type is required to generate a selectivity curve, and it is necessary to make the assumption that both tows encountered the same populations in the same manner, which is unlikely. Analysis of the variance of 60 mm and 70 mm scampi trawl catches indicated that about 330 tows would be required to detect a 10% difference in selectivity using the alternate tow approach, because of large between-tow variation (Kirkegaard et al. 1989). Kirkegaard also used these data to suggest that only 55 tows would be needed to estimate a 10% difference when the twin tow approach was used. In this approach, two nets are rigged side-by-side and towed at the same time and, hence, are more comparable. Similar results are likely using the trouser trawl method, in which a trawl is vertically divided down the middle, with a codend for each side. Because of large between-tow variability, both the twin and trouser trawl methods still require a large number of tows to assess selectivity of a single pair of gear types. If triple rigs are used, the fishing power of the three nets should not be considered equal, as the herding effects of the warps and wings is likely to result in higher catches of finfish in the centre net. The fishing power of the outer two nets may be considered equal if a modification to one of the nets does not significantly affect the configuration of that net during fishing. Finally, the parallel tow approach involves the indirect comparison of catches from two (supposedly identical) vessels, each trawling in an identical manner, and towing similar nets, one of which is modified with the intention of improving its performance.

All these assessment methods have their disadvantages. Ultimately, the type of bycatch reduction gear investigated will determine the choice of experimental approach used. These choices will, in turn, be determined by the specified management objectives.

4.5 Potentially suitable approaches for New Zealand scampi fisheries

Any attempt to reduce bycatch should be based upon an understanding of how fish behave in, and are selected by trawl gear currently used in the fishery. Commercial fishers currently use a variety of mesh sizes and trawl gear configurations, and these should be identified to ensure that valid comparisons of experimental gears are made with those used operationally. Ideally, an agreed "standard gear type" would then be developed, which could be duplicated or modified.

Currently, the "standard gear type" is likely to be double or triple rigged trawl nets, with the wings and belly of each net constructed of 100 mm mesh, and the codends of 55 or 65 mm mesh. The use of multiple rigs lends itself to the assessment of selectivity using a paired tow approach similar to that used by Kirkegaard et al. (1989). In this approach, one of the outer nets would be modified, and resulting catch compared with that of the other outer net. If the modification resulted in lower bycatch ratios (with respect to the catch of marketable scampi), this modification would then be made to the other outer trawl also. Modifications could then be made incrementally, and tested against a sliding baseline of improved bycatch ratios. A final test would be the comparison of a "standard outer trawl gear type", with one that included all tested modifications, and from this the overall gains in bycatch reduction could be assessed.

Modification of one of the outer trawls may result in increased drag on one side of the multiple rig, and any asymmetry in the gear's configuration may invalidate any assumptions made about equal fishing power. Scale models should therefore be tested in a flume tank so that appropriate adjustments can be made to the design prior to field trials. During field trials, long tows of pairs of differently configured gear may result in one trawl with appreciably more catch than the other. The resulting difference in drag, and its influence on the assumption of equal fishing power should, therefore, be avoided by initially towing for shorter distances to ensure that the disparity between catch rates is not too large.

Depending on the construction of the current "standard gear type", the following modifications could be made incrementally to one of the outer trawls to reduce the overall bycatch relative to that of scampi.

- Decrease the mesh in the belly and the wings to 80 mm to test whether the ratio of bycatch weight relative to that of scampi decreases, as suggested by the Bay of Plenty study.
- Increase the codend mesh to 65 mm to see if catch rates of marketable scampi are maintained at a reasonable level while bycatches of small finfish species are reduced, as suggested by the Bay of Plenty study.
- Increase the codend mesh to 80 mm to see if catch rates of marketable scampi are maintained at a reasonable level while bycatches of small finfish species are reduced still further.
- Include a square mesh escape panel in the ceiling of the codend. The positioning of this panel may require both flume tank and field trials with pressure sensors to determine the optimal position.
- Replace the uppermost mesh between the headline and the codend with much larger mesh to permit larger fish with upward escape responses to pass through. This step depends on which species fishers wish to retain, as catch of some valuable quota species may be lost (although it may be desirable to exclude all bycatch when freezer space is limiting).

During field trials, observations of fish behaviour could be made by infra-red video cameras fixed onto the centre net (if a triple rig is used). Observations of fish behaviour may provide insights into which approaches may be suitable to reduce the bycatch of the species observed.

4.6 Implementation and industry involvement

The fishing industry should be involved in all stages of development of any bycatch reduction technology to ensure that the final approach taken is practical, reliable and acceptable to commercial fishers (e.g., Goethel 1996, Kennelly & Broadhurst 1996). Kennelly (2000) stated that "*The overriding and simple message ... is that the sooner industry are fully involved in all stages of the work (driving the issue, quantifying it, developing new gears and implementing them), the sooner and more complete is the voluntary acceptance of new sustainable fishing technologies.*" Thus, international experience suggests that the following steps (Kennelly & Broadhurst 2002) are necessary for the incremental development and implementation of any approach:

- identifying the main discard catch species of concern
- development of technological modifications that minimise the mortality of these species
- comparisons of the alternative approaches with existing industry practice
- implementing these solutions throughout the industry
- gaining acceptance of the solutions by all parties

The first step has been largely achieved through the existing scientific observer programme, which has been operating in the scampi fishery since 1989. Localised issues, such as the bycatch of juvenile ling in QMA 6A, have been identified and these could be addressed individually. However, the scale and diversity of the bycatch in all scampi fisheries suggests that an approach which reduces the overall bycatch while maintaining scampi catch rates should be developed first. Regional or species-specific bycatch issues could then be reassessed once subsequent bycatches are quantified.

Development of technological modifications or changes to fishing practice should take place with industry involvement for two reasons. Firstly, some fishers have already experimented with some approaches in an informal manner, and this experience may highlight areas that should, or should not, be pursued. Secondly, any approach that is developed should be trialled on commercial vessels to ensure that the technology is reliable, practical, and generally consistent with current practice.

5. CONCLUSIONS

1. Trawlers targeting scampi in New Zealand take a wide variety of bycatch species, most of which are discarded. This fishery discards roughly an order of magnitude more weight of fish bycatch per unit target catch than any of the other fisheries studied in New Zealand (hoki, orange roughy, southern blue whiting, jack mackerels, and squid). This is typical of many crustacean fisheries worldwide.

2. The total weight of bycatch discarded by the scampi trawl fishery is more than that discarded by the much bigger (by catch weight) orange roughy and southern blue whiting fisheries, but less than is discarded by the hoki and squid fisheries.

3. Survivorship of discards is likely to be taxon-specific and difficult to assess experimentally. However, given the great depth, the long tows, and the relatively slow processing of the catch, we think that survival of discarded finfish is likely to be negligible.

4. A review of the international literature suggests that approaches to reducing bycatch worldwide have focussed on either changing mesh sizes or incorporating various escape devices in the trawl net to exploit behavioural differences in target and bycatch species. Suitably placed coarse-mesh or square-mesh panels, and various grids and excluder devices have been found to be the most successful in scampi fisheries.

5. Two formal studies of scampi trawl selectivity have been completed in New Zealand, both in the western Bay of Plenty, on Nordmøre grids in 1992, and on codend and body mesh selectivity in 1996. Many informal trials have been conducted by industry with some success, and some methods of reducing bycatch have been generally adopted. No data were made available for analysis, however.

6. In the 1992 Nordmøre grid study, the weight of skate in the catch was the predominant factor affecting the performance of this method. Large skates apparently interfered with the selectivity characteristics of the grid and resulted in an appreciable loss of scampi (average 13% by weight, about 15% by value) from the catch. Nonetheless, the grid was successful in diverting over 80% of the bycatch of large fish from the catch, and about 30% of the small fish. No differences were detected among different bar spacings or angles of attack for the grids.

7. In the 1996 codend mesh study, only six species were sufficiently numerous to estimate codend selectivity: scampi, silver roughy, javelinfish, "other rattails", sea perch, and capro dory. Some small javelinfish and "other rattails" were allowed through to the cover by all three meshes tested (30, 55, and 65 mm), but the 65 mm mesh allowed most fish to pass through. The finer codends fully retained all silver roughy, sea perch, and capro dories, but the 65 mm codend allowed some smaller fish of these species through. All meshes tested fully retained the most abundant scampi length classes. Our estimated selectivity curves are based

on short (3 nautical mile) tows, and clogging towards the end of longer commercial tows may affect selectivity.

8. In the 1996 body mesh study, there were significant differences in the catch rates of scampi and sea perch using trawls constructed of 80 and 100 mm mesh. Trawls constructed of 80 mm mesh caught less bycatch per kilogram of scampi than those constructed of 100 mm mesh. Because scampi catches are constrained by annual catch entitlements, the use of nets constructed of 80 mm mesh (as opposed to 100 mm) would probably result in a lower overall bycatch because less trawling effort would be required to reach the catch limits. Unobserved incidental effects such as habitat modification are also likely to be reduced.

9. The approach taken to reduce bycatch in New Zealand scampi fisheries will ultimately be determined by the management objectives of these fisheries. This is not a step that can be undertaken by a research provider and should, ideally, involve managers and all stakeholders in the fishery. Once management objectives are clearly defined, appropriate bycatch reduction approaches can be investigated, and performance standards set. Nonetheless, some broad considerations are outlined in this document, based on New Zealand and overseas studies.

10. The fishing industry should be involved in all stages of the development any bycatch reduction technology to ensure that the final approach taken is practical, reliable, and safe.

6. ACKNOWLEDGMENTS

We sincerely thank Vaughan Wilkinson and Neil Penwarden for frank and open discussions of scampi trawling as undertaken by Simunovich Fisheries and Barine Developments at a time of considerable political tension in the fishery. We are also grateful to Dave Allen, Keith Michael, Dean Stotter, Jonathon Ingerson, Dick Singleton, Jeremy McKenzie, Mark Morrison, Malcolm Haddon, and the skippers and crews of M.F.V. *Mutual Enterprise* and R.V. *Kaharoa* for their efforts in the 1992 and 1996 bycatch reduction studies. We thank Suze Baird for many useful comments on a draft of this report. This study was funded under Ministry of Fisheries contract ENV2001/07, *Reducing bycatch in scampi trawl fisheries*.

7. REFERENCES

Alverson, D.L.; Freeberg, M.H.; Murawski, S.A.; Pope, J.G. (1994). A global assessment of fisheries bycatch and discards. *FAO Technical Paper #339*. FAO, Rome.

Anderson, O.F. (2004). Fish discards and non-target catch in the trawl fisheries for arrow squid, jack mackerel, and scampi in New Zealand waters. *New Zealand Fisheries Assessment Report 2004/10*. 61 p..

Anderson, O.F.; Clark, M.R.; Gilbert, D.J. (2000). Bycatch and discards in trawl fisheries for jack mackerel and arrow squid, and in the longline fishery for ling, in New Zealand waters. *NIWA Technical Report 74*. 44 p.

Anderson, O.F.; Gilbert, D.J.; Clark, M.R. (2001). Fish discards and non-target catch in the trawl fisheries for orange roughy and hoki in New Zealand waters for the fishing years 1990–91 to 1998–99. *New Zealand Fisheries Assessment Report 2001/16*. 57 p.

Andrew, N.L.; Graham, K.J.; Kennelly, S.J; Broadhurst, M.K. (1991). The effects of trawl configuration on the size and composition of catches using benthic prawn trawls of the coast of New South Wales, Australia. *ICES Journal of Marine Science 48*: 201–209.

Andrew, N.L.; Kennelly, S.J; Broadhurst, M.K. (1993). An application of the Morrison soft TED to the offshore prawn fishery in New South Wales, Australia. *Fisheries Research 16*: 101–111.

Andrew, N.L.; Pepperell (1992). The bycatch of shrimp trawl fisheries. *Oceanography and Marine Biology Annual Review* 30: 527–565.

Annala, J.H.; Sullivan, K.J.; Smith, N.W.McL.; Griffiths, M.H.; Todd, P.R.; Mace, P.M.; Connell, A.M. (Comps.) (2004). Report from the Fishery Assessment Plenary, April 2004: stock assessments and yield estimates. 690 p. (Unpublished report held in NIWA library, Wellington.)

Armstrong, M.J.; Briggs, R.P.; Rihan, D. (1998). A study of optimum positioning of square-mesh escape panels in Irish Sea *Nephrops* trawls. *Fisheries Research 34*: 179–189.

Bartley, D.M. (1998a). *Ex situ* conservation, gene banks, and responsible fisheries. *In*: Action Before Extinction, World Fisheries Trust, Victoria, Canada, pp. 45–55.

Bartley, D. (1998b). Policies for the conservation and sustainable use of aquatic genetic resources. *FAO Aquaculture Newsletter 19*: 8–9.

Bergmann, M.; Wieczzorek, S.K.; Moore, P.G.; Atkinson, R.J.A. (2002). Discard composition of the *Nephrops* fishery in the Clyde Sea area, Scotland. *Fisheries Research 57*: 169–183.

Blaber, S.; Brewer, D.; Buckworth, R.; Burridge, C.; Farmer, M.; Milton, D.; Salini, J.; Wang, Y.; Wassenberg, T.; Buxton, C.; Cartwright, I.; Eayrs, S.; Rawlinson, N.; Gill, N.; Mounsey, R.; Ramm, D.; MacCartie, J. (1997). Effects of trawl design on bycatch and benthos in prawn and finfish fisheries. Final Research Report Project FRDC 93/179. 190 p. (Unpublished report held in NIWA library, Wellington.)

Booth, J.D.; Baird, S.J.; Stevenson, M.L.; Bagley, N.W.; Wood, B.A. (2002). Review of technologies and practices to reduce bottom trawl bycatch and seafloor disturbances in New Zealand. Final Research Report to MFish on project ENV2001/06. (Unpublished report held by MFish, Wellington.)

Brewer, D.; Eayrs, S.; Rawlinson, N. (1995). Bycatch reduction devices show promise in the NPF. *Australian Fisheries, May*: 24–25.

Briggs, R.P. (1986). A general review of mesh selection for *Nephrops norvegicus* (L.). *Fisheries Research 4*: 59–73.

Briggs, R.P. (1992). An assessment of nets with a square mesh panel as a whiting conservation tool in the Irish Sea *Nephrops* fishery. *Fisheries Research 3*: 133–152

Broadhurst, M.K. (2000). Modifications to reduce bycatch in prawn trawls: a review and framework for development. *Reviews in Fish Biology and Fisheries 10*: 27–60.

Broadhurst, M.K.; Kangas, M.I.; Damiano, C.; Bickford, S.A.; Kennelly, S.J. (2002). Using composite square-mesh panels and the Nordmøre grid to reduce bycatch in the Shark Bay prawn-trawl fishery, Western Australia. *Fisheries Research 58*: 349–365.

Broadhurst, M.K.; Kennelly, S.J. (1996). Rigid and flexible separator panels in trawls that reduce the bycatch of small fish in the Clarence River prawn-trawl fishery. *Marine and Freshwater Research 47*: 991–998.

Broadhurst, M.K.; Kennelly, S.J.; Gray, C.A. (2002). Optimal positioning and design of behavioural-type bycatch reduction devices involving square-mesh panels in penaeid prawn-trawl codends. *Marine and Freshwater Research 53*: 813–823.

Broadhurst, M.K.; Kennelly, S.J.; Watson, J.W.; Workman, I.K. (1997). Evaluations of the Nordmøre grid and secondary bycatch reducing devices (BRD's) in the Hunter River prawn-trawl fishery, Australia. *Fishery Bulletin 95*: 209–218.

Broadhurst, M.K.; Larsen, R.B.; Kennelly, S.J.; McShane, P.E. (1999). Use and success of composite square–mesh codends in reducing bycatch and in improving size–selectivity of prawns in Gulf St. Vincent, South Australia. *Fisheries Bulletin 97*: 434–448.

Broadhurst, M.K.; McShane, P.E.; Larsen, R.B. (1997). Effects of twine diameter and mesh size in the body of prawn trawls on bycatch in Gulf St. Vincent, Australia. *Fishery Bulletin 98*: 463–473.

Caddy, J.F. (1996). A checklist for fisheries resource management issues seen from the perspective of the F.A.O. Code of Conduct for Responsible Fisheries. *F.A.O. Fisheries Circular 917*. 22 p.

Campos, A.; Fonseca, P. (2004). The use of separator panels and square mesh windows for bycatch reduction in the crustacean trawl fishery off the Algarve (South Portugal). *Fisheries Research 69*: 147–156.

Campos, A.; Fonseca, P.; Erzini, K. (2003). Size selectivity of diamond and square mesh codends for four bycatch species in the crustacean fishery off the Portuguese south coast. *Fisheries Research 60*: 79–97.

Crowley, M. (2001). Tinkering with trawls. *National Fisherman*, November, 2001: 46–47.

Cryer, M. (2000). A consideration of current management areas for scampi in QMAs 3, 4, 6A, and 6B. Final Research Report for Ministry of Fisheries Project MOF1999/04K: Objective 1. 52 p. (Unpublished report available from Ministry of Fisheries, Wellington).

Cryer, M.; Coburn, R. (2000). Scampi stock assessment for 1999. *New Zealand Fisheries Assessment Report 2000/07*. 60 p.

Cryer, M.; Coburn, R.; Hartill, B.; O'Shea, S.; Kendrick, T.; Doonan, I. (1999). Scampi stock assessment for 1998 and an analysis of the fish and invertebrate bycatch of scampi trawlers. New Zealand Fisheries Assessment Research Document 99/4. 75 p. (Unpublished report held in NIWA library, Wellington).

Cryer, M.; Doonan, I.; Coburn, R.; Hartill, B. (1998). Scampi stock assessment for 1997. New Zealand Fisheries Assessment Research Document 98/28. 77 p. (Unpublished report held in NIWA library, Wellington).

Cryer, M.; Hartill, B. (2002). Relative impacts on benthic invertebrate community structure of trawl fisheries for scampi and finfish in the Bay of Plenty. Final Research Report for Ministry of Fisheries Research Project ENV2000/05: Objective 2. 28 p. (Unpublished report available from Ministry of Fisheries, Wellington).

Cryer, M.; Hartill, B.; Drury, J. (2001). Photographic estimation of the abundance and biomass of scampi, *Metanephrops challengeri*. Final Research Report for Ministry of Fisheries Research Project SCI1999/02. 34 p. (Unpublished report available from Ministry of Fisheries, Wellington).

Cryer, M.; Hartill, B.; O'Shea, S. (2002). Modification of marine benthos by trawling: toward a generalization for the deep ocean? *Ecological Applications 12*: 1824–1839.

Cryer, M.; Oliver, M. (2001). Estimating age and growth in New Zealand scampi, *Metanephrops challengeri*. Final Research Report for Ministry of Fisheries Research Project SCI9802, Objective 2. 56 p. (Unpublished report held by Ministry of Fisheries, Wellington).

Cryer, M.; Stotter, D.R. (1997). Trawling and tagging of scampi off the Aldermen Islands, western Bay of Plenty, September 1995 (KAH9511). *New Zealand Fisheries Data Report 84*. 11 p.

Dayton, P.K.; Thrush, S.F.; Agardy, M.T.; Hofman, R.J. (1995). Environmental effects of fishing. *Aquatic Conservation: Marine and Freshwater Ecosystems 5*: 205–232.

Engås, A.; Sodal, A.V. (1992). Diurnal variations in bottom trawl catch rates of cod and haddock and their influence on abundance indices. *ICES Journal of Marine Science 49*: 89–95.

Engås, A.; West, C.W. (1995). Development of a species–selective trawl for demersal gadoid fisheries. ICES CM 1995/B+G+H+J+K:1 20 p.

Evans, S.M.; Hunter, J.E.; Elizal; Wahju, R.I. (1994). Composition and fate of the catch and bycatch in the Farne Deep (North Sea) *Nephrops* fishery. *ICES Journal of Marine Science 51*: 155–168

Fonds, M. (1994). Mortality of fish and invertebrates in beam trawl catches and the survival chances of discards. *In*: de Groot, S.J.; Lindeboom, H.L. (eds), Environmental impact of bottom gears on benthic fauna in relation to natural resources management and protection of the North Sea. NIOZ-Rapport 1994–11/RIVO–DLO Report CO 26/94.

Galbraith, R.D.; Main, J. (1989). Separator panels for dual purpose fish/prawn trawls. *Scottish Fisheries Information Pamphlet 16*: 8 p.

Goethel, David (1996). A fisherman's perspective on the Nordmøre grate. Proceedings of the East Coast Bycatch Conference, Rhode Island Sea Grant, December 1996, pp. 76–77.

Graham, N.; Kynoch, R.J. (2001). Square mesh panels in demersal trawls: some data on haddock selectivity in relation to mesh size and position. *Fisheries Research 49*: 207–218.

Hall, S.J. (1999). The effects of fishing on marine ecosystems and communities. Blackwell Scientific, Oxford, England.

Halliday, R.G.; Cooper, C.G. (1999). Evaluation of separator grates for reduction of bycatch in the silver hake (*Merluccius bilinearis*) otter trawl fishery off Nova Scotia, Canada. *Fisheries Research 40*: 237–249.

Hartill, B.; Cryer, M. (2000). A review of the adequacy of the current observer coverage and practices for scampi. Final Research Report for Ministry of Fisheries Research Project MOF199904J, Objective 1. 40 p. (Unpublished report held by Ministry of Fisheries, Wellington).

Hemmings, C.C. (1973). Direct observation of the behaviour of fish in relation to fishing gear. *Hegolander Wissenschaftliche Meeresunterschungen 24*: 348–360.

Hill, B. J.; Wassenberg, T.J. (2000). The probable fate of discards from prawn trawlers fishing near coral reefs: A study in the northern Great Barrier Reef, Australia. *Fisheries Research 48*: 277–286.

Holt, E.W.L. (1895). An examination of the present state of the Grimsby trawl fishery, with special reference to the destruction of immature fish. The Marine Biological Association Plymouth. New Series. Vol III (v).

Hongskul,V. (1979). Report on the studies of multi-species systems in fisheries. *In*: *FAO Fisheries Circular # 718*, Interim Report of the ACMRR Working Party on the Scientific Basis of Determining Management Measures. FAO, Rome, pp. 73–84.

Howard, F.G. (1989). The Norway lobster. *Scottish Fisheries Information Pamphlet 7*: 15 p.

Isaksen, B. (1997). The Norwegian approach to reduce bycatch and avoid discards. FAO Fisheries Report 547, Supplementary, 89–93. (Proceedings of Technical Consultation on Reduction of Wastage in Fisheries, Tokyo, Japan, October-November 1996).

Isaksen, B.; Valdemarsen, J.W.; Larsen, R.B.; Karlsen, L. (1992). Reduction of fish bycatch in shrimp trawl using a rigid separator grid in the aft belly. *Fisheries Research 13*: 335–352.

Jennings, S.; Dinmore, T.A.; Duplisea, D.E.; Warr, K.J.; Lancaster, J.E. (2001). Trawling disturbance can modify benthic production processes. *Journal of Animal Ecology 70*: 459–475.

Jennings, S.; Nicholson, M.D.; Dinmore, T.A.; Lancaster, J.E. (2002). Effects of chronic trawling disturbance on the production of infaunal communities. *Marine Ecology Progress Series 243*: 251–260.

Kennelly, S.J. (2000). The Australian procedure and experience with the introduction and acceptance of new sustainable fishing technologies. (Papers presented at the Expert Consultation on Sustainable Fishing Technologies and Practices. St. John's, Newfoundland, Canada, 1–6 March 1998.) *FAO Fisheries Report 588* (Supplement): 106–122.

Kennelly, S.J.; Broadhurst, M.K. (1996). Fishermen and scientists solving bycatch problems: Examples from Australia and possibilities for the northeastern United States. Proceedings of the Solving Bycatch Workshop, September 25–27, 1995, Seattle, Washington. Alaska Sea Grant College Program, Fairbanks, AK (USA), 1996, pp. 121–128.

Kennelly, S.J.; Broadhurst, M.K. (2002). Bycatch begone: changes in the philosophy of fishing technology. *Fish and Fisheries 3*: 340–355.

Kirkegaard, E.; Nielsen, N.A.; Bagge, O. (1989). Mesh selection of *Nephrops* in 60 and 70 mm *Nephrops* trawl. ICES Council meeting (Collected papers)., ICES, Copenhagen (Denmark) , 1989, 22 p.

Linnane, A.; Ball, B.; Munday, B.; van Marlen, B.; Bergman, M.; Fonteyne, R. (2000). A review of potential techniques to reduce the environmental impact of demersal trawls. *Irish Fisheries Investigations (New Series) No. 7.* 39 p.

Madsen, N.; Hansen, K.E. (2001). Danish experiments with a grid system tested in the North Sea shrimp fishery. *Fisheries Research 52*: 203–216.

Madsen, N.; Hansen, K.E.; Moth-Poulsen, T. (2001). The kite cover: a new concept for covered codend selectivity studies. *Fisheries Research 49*: 219–226.

Madsen, N.; Moth-Poulsen, T.; Holst, R.; Wileman, D. (1999). Selectivity experiments with escape windows in the North Sea neprops (*Nephrops norvegicus*) trawl fishery. *Fisheries Research 42*: 167–181.

Main, J.; Sangster, G.I. (1985). Trawling experiments with a two-level net to minimise the undersized gadoid bycatch in a *Nephrops* fishery. *Fisheries Research 3*: 131–145.

Robertson, J.H.B. (1987). Design and construction of square mesh codends. *Scottish Fisheries Information Pamphlet 12*: 10 p.

Robertson, J.H.B.; Emslie, D.C.; Ballantyne, K.A.; Chapman, C.J. (1986). Sqaure and diamond mesh trawl codend selection trials on *Nephrops norvegicus* (L). International Council for the Exploration of the Sea, CM 1986/B:12, 5 p.

Robertson, J.H.B.; Shanks, A.M. (1987). Size selection of *Nephrops* by four different types of codend. Scottish Fisheries Working Paper 12/87: 14 p.

Robertson, J.H.B.; Shanks, A.M. (1994). The effects on catches of *Nephrops*, haddock and whiting of square mesh window position in a *Nephrops* trawl. ICES CM 1994/B:32, Fish Capture Committee.

Robins, J.B.; Campbell, M.J.; McGilvray, J.G. (1999). Reducing prawn-trawl bycatch in Australia: an overview and an example from Queensland. *Marine Fisheries Review 61*: 46–55.

Robins, J.B.; McGilvray, J.G. (1999). The AusTED II, an improved trawl efficiency device 2. Commercial performance. *Fisheries Research 41*: 29–41.

Robins-Troeger, J.B. (1994). Evaluation of the Morrison soft turtle excluder device: prawn and bycatch variation in Moreton Bay, Queensland. *Fisheries Research 19*: 205–217.

Sainsbury, J. C. (1996). Commercial fishing methods. Third edition. Fishing News Books. 368 p.

Salini, J.; Brewer, D.; Farmer, M.; Rawlinson, N. (2000). Assessment and benefits of damage reduction in prawns due to use of different bycatch reduction devices in the Gulf of Carpentaria, Australia. *Fisheries Research 45*: 1–8.

Sarda, F.; Conan, G.Y.; Fuste, X. (1993). Selectivity of Norway lobster *Nephrops norvegicus* (L). in the northwestern Mediterranean. *Scientifica Marina 57*: 167–174.

Sobrino, I.; Garcia, T.; Baro, J. (2000). Trawl gear selectivity and the effect of mesh size on the deep-water rose shrimp (*Parapenaeus longirostris*, Lucas 1846) fishery off the gulf of Cadiz (SW Spain). *Fisheries Research 44*: 235–245.

Stergiou, K.I.; Politou, C.Y.; Christou, E.D.; Petrakis, G. (1997). Selectivity experiments in the NE Mediterranean: the effects of trawl codend mesh size on species diversity and discards. *ICES Journal of Marine Science 54*: 774–786.

Stewart, P.A.M.; Galbraith, R.D. (1989). Codend design, selectivity and legal definitions. ICES CM/B:11. 7 p.

Thomas, H.J. (1965). A comparison of the catch of Norway lobsters using trawls of 50 mm and 70 mm respectively. *Rapports et Process Verbeaux de la Réunion Conseil Internationale pour l'Exploration de la Mer 156*: 206–208.

Thorsteinsson, G. (1992). The use of square mesh codends in the Icelandic shrimp (*Pandalus borealis*) fishery. *Fisheries Research 13*: 255–266.

Thrush, S.F.; Hewitt, J.E.; Cummings, V.J.; Dayton, P.K.; Cryer, M.; Turner, S.J.; Funnell, G.A.; Budd, R.G.; Milburn, C.J.; Wilkinson, M.R. (1998). Disturbance of the marine benthic habitat by commercial fishing: impacts at the scale of the fishery. *Ecological Applications 8*: 866–879.

Tuck, I.D.; Hall, S.J.; Robertson, M.R.; Armstrong, E.; Basford, D.J. (1998). Effects of physical trawling disturbance in a previously unfished sheltered Scottish sea loch. *Marine Ecology Progress Series 162*: 227–242.

Vignaux, M.; Gilbert, D.J. (1993). A production model for the FMA 1 scampi fishery, 1989–1991. New Zealand Fisheries Assessment Research Document 93/18. 16 p. (Unpublished report held in NIWA Library, Wellington).

Wardle, C.S. (1995). A review of fish behaviour in relation to species separation and selectivity in mixed fisheries. ICES Joint Session on Improving Species Selectivity in Mixed Species Fisheries CM 1995/B+G+H+J+K:3.

Welcomme, R.L. (1999). A review of a model for qualitative evaluation of exploitation levels in multi-species fisheries. *Fisheries Management & Ecology 6*: 1–19.

Wileman, D.A. (1995). Review of the progress made in Denmark in the development of species selective gears. ICES Joint Session on Improving Species Selectivity in Mixed Species Fisheries CM 1995/B+G+H+J+K:2.

Wileman, D.A.; Ferro, R.S.T.; Fonteyne, R.; Millar, R.B. (1996) Manual of methods of measuring the selectivity of towed fishing gears. *ICES Cooperative Research Report 215*: 126 p.

Yaldwyn, J.C. (1954). *Nephrops challengeri* Balss, 1914 (Crustacea, Decapoda, Reptantia) from New Zealand and Chatham Island waters. *Transactions of the Royal Society of New Zealand 82*:721–732.

Ye, Y. (2002). Bias in estimating bycatch-to-shrimp ratios. *Aquatic Living Resources 15*: 149–154.

Zar, J.H. (1996) Biostatistical analysis, 4th ed., Prentice Hall, New York. 929 p.

Appendix 1a: Weight of species or taxa caught by the port net during the Nordmøre grate experiment (kg)

Species	Common name	Total catch (kg)
Metanephrops challengeri	Scampi	778.2
Hoplostethus mediterraneus	Silver roughy	700.0
Helicolenus sp.	Sea perch	433.9
Macruronus novaezelandiae	Hoki	385.7
Lepidorhynchus denticulatus	Javelinfish	344.2
Capromimus abbreviatus	Capro dory	327.5
Raja nasuta	Rough skate	312.3
Phormosoma spp.	Sea urchins	218.2
Macrouridae	Rattails	129.8
Squalus mitsukurii	Northern spiny dogfish	74.9
Genypterus blacodes	Ling	73.3
Pseudophycis bachus	Red cod	66.7
Hoplichthys haswelli	Deepsea flathead	56.2
Torpedo fairchildi	Electric ray	55.6
Gastropoda	Snails	51.1
Cyttus novaezelandiae	Silver dory	35.8
Rexea solandri	Gemfish	31.9
Pseudophycis breviscula	Northern bastard red cod	26.9
Hydrolagus novaezelandia	Ghost shark	25.3
Haliporoides sibogae	Jackknife prawn	23.7
Gollum attenuatus	Slender smooth-hound	22.6
Pentaceros decacanthus	Yellow boarfish	18.4
Seriolella caerulea	White wharehou	16.5
Hemerocoetes spp.	Opalfish	15.9
Etmopterus lucifer	Lucifer dogfish	11.6
Munida gregaria	Munida	10.2
Octopus sp.	Octopus	9.9
Kathetostoma giganteum	Giant stargazer	5.1
Bassanago hirsutus	Hairy conger eel	4.0
Cyttus traversi	Lookdown dory	3.3
Lepidoperca aurantia	Orange perch	2.8
Other		136
TOTAL		4497.5

Appendix 1b: The percentage (by weight) of the ten most common species of commercial importance diverted by the grills to the secondary codend.

Species	Common name	Size range (cm)	% diverted by grill
Squalus acanthias	Spiny dogfish	21–28	100
Galeorhinus australis	School shark	120–150	100
Hyperoglyphe antarctica	Bluenose	50–53	100
Seriolella punctata	Silver warehou	53–56	100
Kathetostoma giganteum	Giant stargazer	45–66	100
Genypterus blacodes	Ling	27–130	97
Macruronus novaezelandiae	Hoki	57–101	81
Rexea solandri	Gemfish	13–88	78
Pseudophycis bachus	Red cod	16–59	55
Metanephrops challengeri	Scampi	1.5–5.8	13
	Total of all catch		38

Appendix 1c: Mean percentage of scampi catch retained in the primary codend (plus and minus 1 standard error in parentheses) in the 1992 experiment. Means back transformed after arcsin transformation, n = 3 in each cell.

Grill bar spacing (mm)	Angle of attack 35°	45°	55°	Mean by row
50	95.0 (98.9; 88.4)	84.5 (95.7; 68.1)	93.7 (96.5; 90.2)	93.6 (95.2; 87.0)
55	88.8 (94.5; 81.3)	70.4 (87.6; 49.5)	84.5 (90.6; 77.2)	81.8 (87.7; 75.1)
60	96.8 (98.3; 94.8)	87.8 (90.0; 85.5)	95.2 (99.0; 88.7)	93.8 (95.8; 91.3)
Mean by column	93.9 (96.2; 91.1)	81.5 (88.0; 73.9)	91.7 (94.5; 88.6)	89.6 (92.0; 86.9)

Appendix 1d: Results of Analysis of Covariance on effects of grill bar spacing, angle of attack, and skate catch (kg), on the percentage of scampi diverted into the secondary (codend + cover). Data arcsin transformed.

Source of variation	df	SS	MS	F	P
Grill (G)	2	413.78	206.89	1.71	0.211
Angle (A)	2	419.31	209.66	1.73	0.207
G*A	4	143.67	143.67	0.30	0.876
Skates	1	721.34	721.34	5.95	0.026
Residual	17	2061.35	2061.35		
Total	26	3990.95			

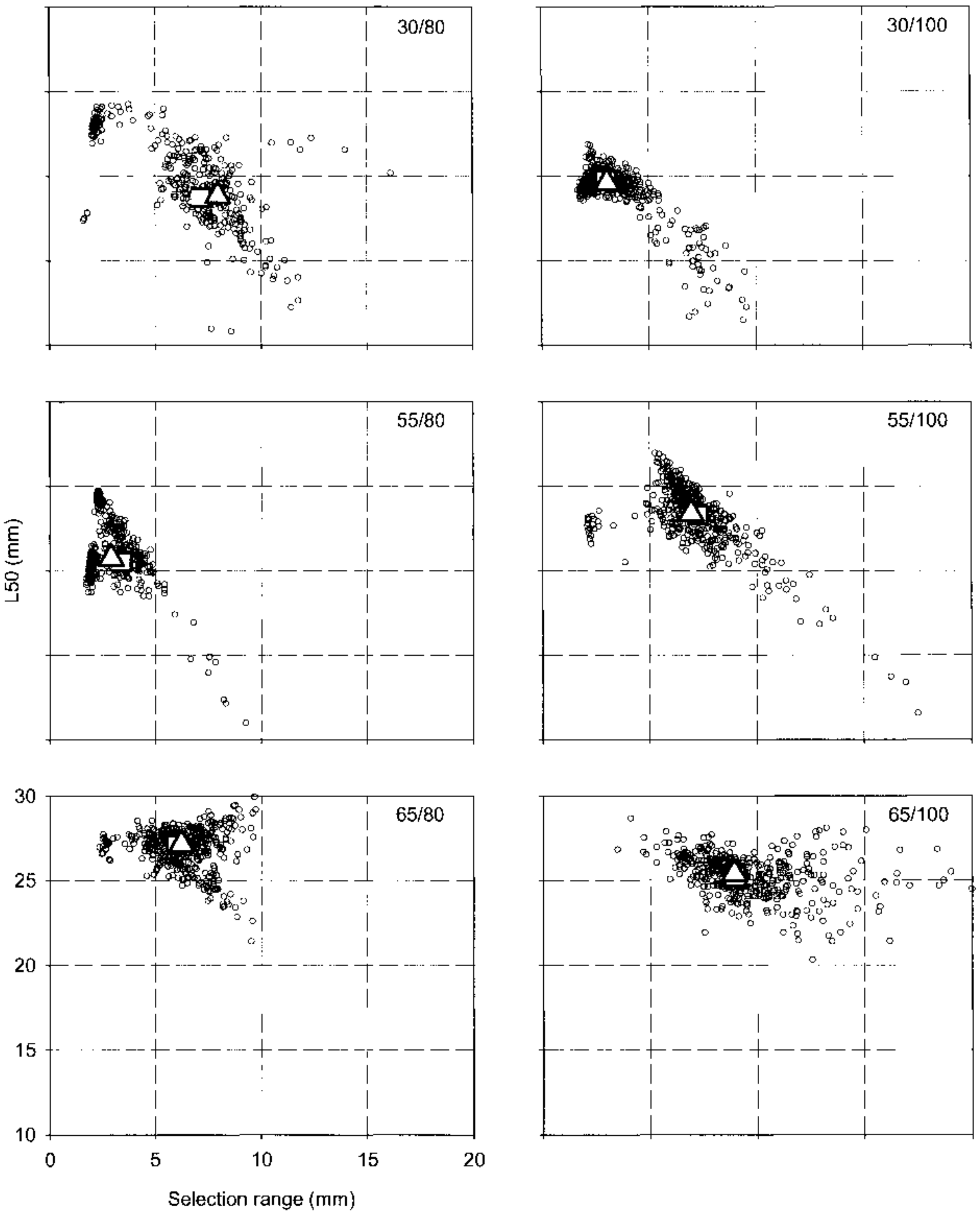
Appendix 1e: Approximate value of scampi caught in the primary and secondary codends.

Scampi grade	OCL (mm)	Wholesale value (NZ$ kg^{-1})	Value of catch retained in primary codend (NZ$)	Value of catch ejected by grill (NZ$)
1	54–60	40.0	513	127
2	46–53	40.0	8 229	1 810
3	43–45	36.5	4 954	775
4	38–42	25.0	4 761	663
5	15–37	19.0	2 837	344
Total			21 294	3 774

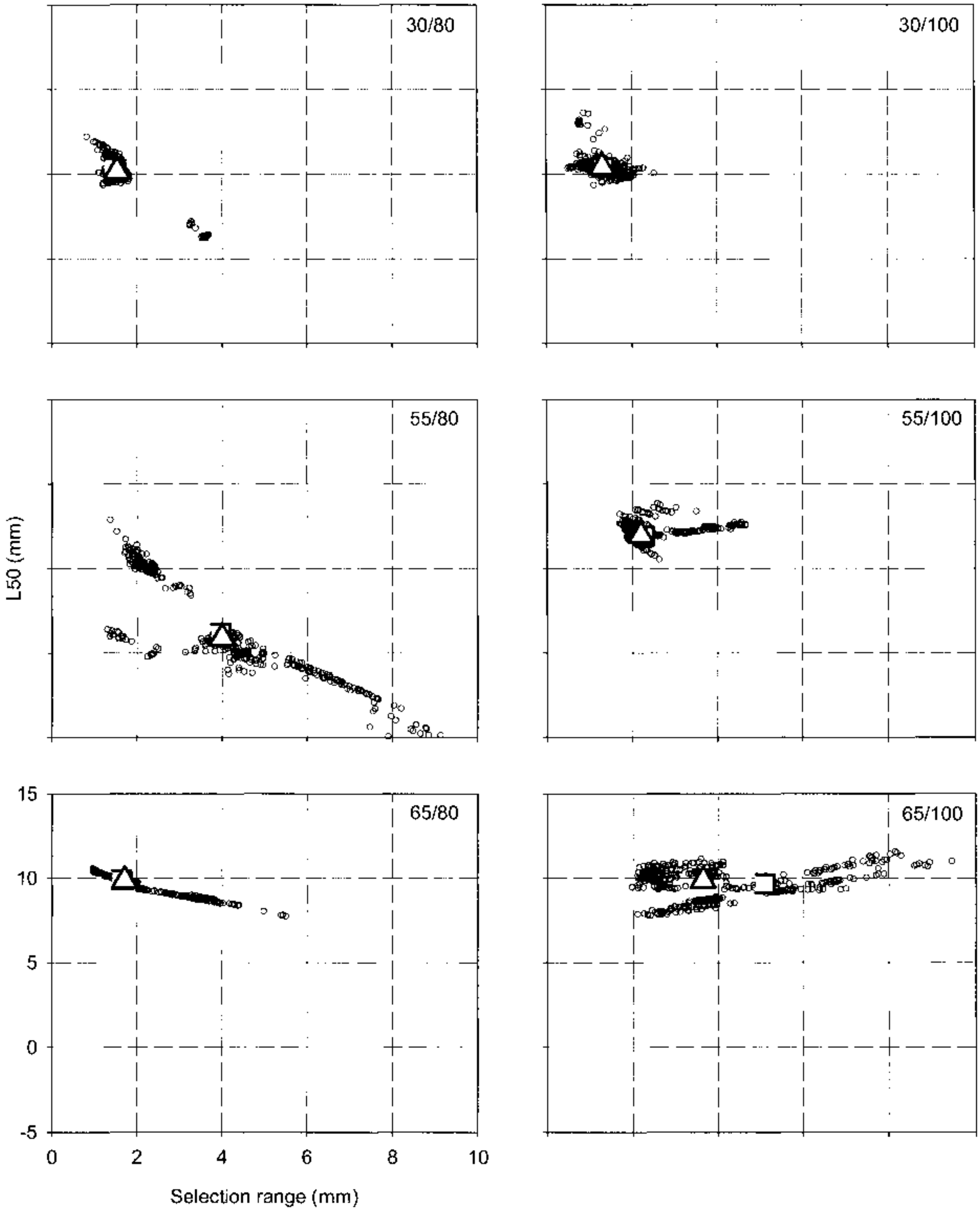
Appendix 2: Numbers of species caught in each combination of codend mesh (30, 55, or 65 mm) and body mesh (80 or 100 mm) during the 1996 NIWA study of mesh selectivity in the western Bay of Plenty (all subcatches and all tows combined for each pairing). Numbers in parentheses are the number of tows (out of 4) from which a species was recorded.

Spp	Common name	Species name	30/80	30/100	55/80	55/100	65/80	65/100
SRH	Silver roughy	*Hoplostethus mediterraneus*	4 651 (4)	833 (4)	18 812 (4)	4 261 (4)	9 957 (4)	866 (4)
JAV	Javelinfish	*Lepidorhynchus denticulatus*	1 747 (4)	1 073 (4)	5 152 (4)	5 843 (4)	1 998 (4)	1 300 (4)
RAT	Rattails	*Macrouridae*	1 013 (4)	891 (4)	2 028 (4)	6 797 (4)	1 474 (4)	598 (4)
SCI	Scampi	*Metanephrops challengeri*	1 142 (4)	915 (4)	4 034 (4)	1 276 (4)	2 464 (4)	672 (4)
SPE	Sea perch	*Helicolenus spp.*	1 734 (4)	775 (4)	1 998 (4)	1 259 (4)	1 900 (4)	1 084 (4)
CDO	Capro dory	*Capromimus abbreviatus*	796 (4)	289 (4)	696 (4)	437 (4)	477 (4)	350 (4)
HOK	Hoki	*Macruronus novaezelandiae*	175 (4)	171 (4)	181 (4)	193 (4)	143 (3)	91 (4)
ETL	Lucifer dogfish	*Etmopterus lucifer*	265 (3)	99 (4)	208 (4)	103 (3)	74 (3)	35 (2)
RCO	Red cod	*Pseudophycis bachus*	125 (3)	42 (4)	138 (4)	82 (4)	75 (4)	26 (4)
FRO	Frostfish	*Lepidopus caudatus*	21 (1)	2 (1)	8 (2)	48 (2)	368 (3)	4 (3)
FHD	Deepsea flathead	*Hoplichthys haswelli*	102 (4)	64 (4)	88 (4)	26 (4)	105 (4)	33 (4)
SSI	Silverside	*Argentina elongata*	49 (4)	34 (4)	58 (4)	51 (4)	34 (4)	64 (4)
BRC	Northern bastard cod	*Pseudophycis breviuscula*	42 (4)	12 (3)	23 (3)	56 (2)	89 (4)	18 (4)
YBO	Yellow boarfish	*Pentaceros decacanthus*	22 (4)	20 (4)	52 (4)	8 (4)	36 (4)	14 (4)
MDO	Mirror dory	*Zenopsis nebulosus*	16 (4)	9 (2)	43 (4)	58 (4)	10 (3)	11 (4)
APG	Cardinalfish	*Apogonidae*	29 (4)	16 (3)	62 (4)	4 (1)	23 (3)	7 (3)
TOP	Pale toadfish	*Neophrynichthys angustus*	39 (4)	9 (4)	14 (3)	4 (1)	24 (2)	8 (2)
LIN	Ling	*Genypterus blacodes*	11 (4)	15 (4)	32 (4)	8 (4)	12 (3)	9 (3)
SCO	Swollenhead conger	*Bassanago bulbiceps*	23 (3)	4 (3)	17 (4)	15 (4)	10 (4)	9 (4)
GSH	Ghost shark	*Hydrolagus novaezealandiae*	30 (2)	–	7 (2)	17 (3)	7 (3)	16 (2)
SDF	Spotted flounder	*Azygopus pinnifasciatus*	20 (4)	10 (3)	16 (3)	7 (3)	10 (4)	8 (2)
LAN	Lantern fish	*Myctophidae*	36 (2)	–	11 (2)		2 (1)	–
SKI	Gemfish	*Rexea solandri*	3 (1)	6 (3)	10 (4)	8 (3)	8 (2)	6 (3)
CUC	Cucumber fish	*Chlorophthalmus nigripinnis*	1 (1)	1 (1)	13 (2)	7 (2)	6 (1)	9 (4)
LDO	Lookdown dory	*Cyttus traversi*	–	1 (1)	14 (3)	1 (1)	14 (2)	–
NOS	Arrow squid	*Nototodarus sloanii*	2 (2)	3 (3)	–	4 (2)	12 (3)	7 (3)
HAT	Hatchetfish	*Sternoptychidae*	5 (2)	–	–	3 (2)	6 (1)	–
EUC	Eucla cod	*Euclichthys polynemus*	2 (1)	1 (1)	4 (2)	–	6 (2)	–
HAG	Hagfish	*Eptatretus cirrhatus*	6 (1)	–	1 (1)		–	–
OSE	Snake eel	*Ophisurus serpens*	4 (1)	–	–		1 (1)	2 (1)
ZDO	Zenion dory	*Zenion leptolepis*	1 (1)	2 (2)	2 (2)		–	1 (1)
BTA	Pavoraja asperula	*Pavoraja asperula*	–	1 (1)		2 (1)	1 (1)	–
NSD	Northern spiny dogfish	*Squalus mitsukurii*	1 (1)	1 (1)		1 (1)	1 (1)	
OPA	Opalfish	*Hemerocoetes* spp	2 (1)	1 (1)		–		
SND	Shovelnose spiny dogfish	*Deania calcea*	–		3 (1)	–		–
SQU	Arrow squid	*Nototodarus sloanii & N. gouldi*	–	–	1 (1)	–	2 (1)	–
CAR	Carpet shark	*Cephaloscyllium isabellum*	1 (1)	–	–	1 (1)	–	–
JGU	Spotted gurnard	*Pterygotrigla picta*	–	1 (1)	–	1 (1)	–	–
OPE	Orange perch	*Lepidoperca aurantia*	2 (1)	–	–	–	–	–
UNI	Unidentified		1 (1)	1 (1)	–	–	–	–
BAS	Bass groper	*Polyprion americanus*	–	–	–	–	1 (1)	–
BRZ	Brown stargazer	*Xenocephalus armatus*	–	–	–	1 (1)	–	–
BYX	Alfonsino & long-finned beryx	*Beryx splendens & B. decadactylus*	–	–	–	1 (1)	–	–
CON	Conger eel	*Conger* spp	–	–	–	–	1 (1)	–
RHY	Common roughy	*Paratrachichthys trailli*	–	–	–	–	–	1 (1)
SSH	Slender smooth-hound	*Gollum attenuatus*	–	–	–	–	–	1 (1)
Total catch			12 119	5 303	33 726	20 583	19 351	5 250

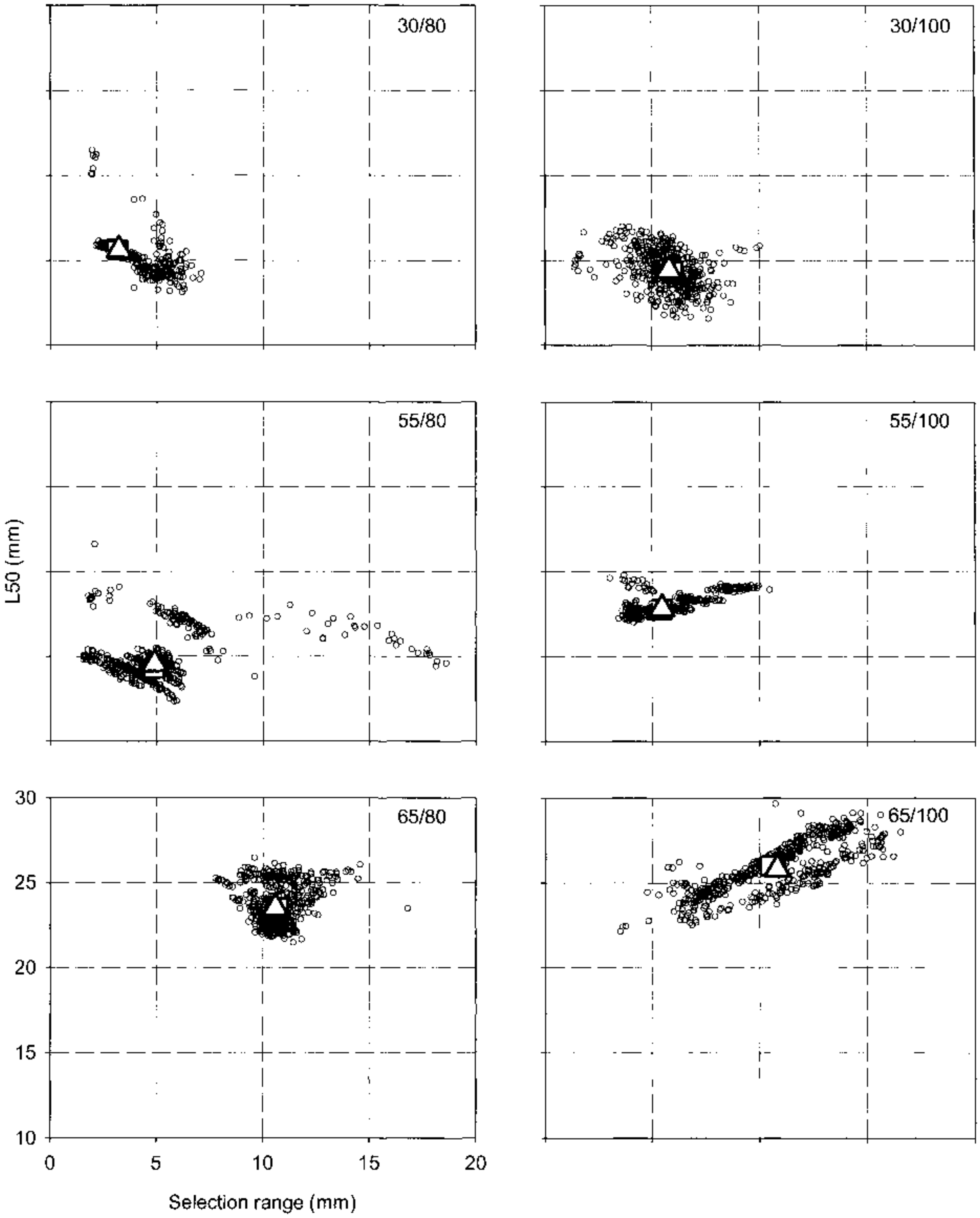
Appendix 3a: Distribution of bootstrap estimates of L_{50} and the selection range for scampi under six different combinations of codend mesh (30, 55, or 65 mm) and body mesh (80 or 100 mm) during the 1996 NIWA study of mesh selectivity in the western Bay of Plenty. Large squares denote the fit to the raw data and large triangles the median bootstrap estimates of L_{50} and the selection range. Some extreme outliers are not shown.



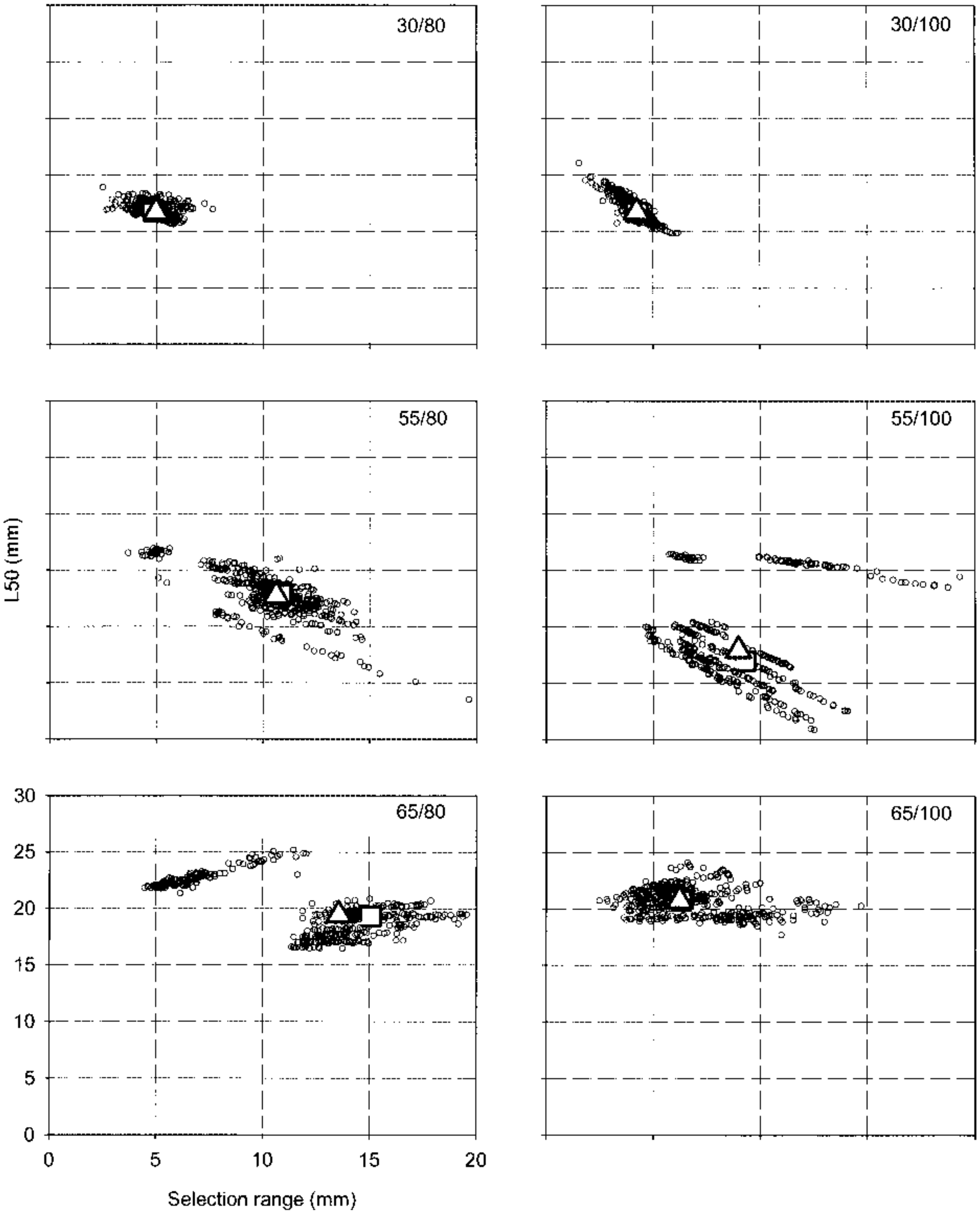
Appendix 3b: Distribution of bootstrap estimates of L_{50} and the selection range for silver roughy under six different combinations of codend mesh (30, 55, or 65 mm) and body mesh (80 or 100 mm) during the 1996 NIWA study of mesh selectivity in the western Bay of Plenty. Large squares denote the fit to the raw data and large triangles the median bootstrap estimates of L_{50} and the selection range. Some extreme outliers are not shown.



Appendix 3c: Distribution of bootstrap estimates of L_{50} and the selection range for javelinfish under six different combinations of codend mesh (30, 55, or 65 mm) and body mesh (80 or 100 mm) during the 1996 NIWA study of mesh selectivity in the western Bay of Plenty. Large squares denote the fit to the raw data and large triangles the median bootstrap estimates of L_{50} and the selection range. Some extreme outliers are not shown.



Appendix 3d: Distribution of bootstrap estimates of L_{50} and the selection range for "other rattails" (i.e., excluding javelinfish) under six different combinations of codend mesh (30, 55, or 65 mm) and body mesh (80 or 100 mm) during the 1996 NIWA study of mesh selectivity in the western Bay of Plenty. Large squares denote the fit to the raw data and large triangles the median bootstrap estimates of L_{50} and the selection range. Some extreme outliers are not shown.



Appendix 3e: Distribution of bootstrap estimates of L_{50} and the selection range for sea perch under six different combinations of codend mesh (30, 55, or 65 mm) and body mesh (80 or 100 mm) during the 1996 NIWA study of mesh selectivity in the western Bay of Plenty. Large squares denote the fit to the raw data and large triangles the median bootstrap estimates of L_{50} and the selection range. Some extreme outliers are not shown.