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RESEARCH PAPER

Gear technology in *Nephrops* trawl fisheries

T. L. Catchpole · A. S. Revill

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Abstract Nets with a small mesh size are required to catch *Nephrops norvegicus*, consequently large quantities of small whitefish are also caught, and much of this bycatch is undersized and is discarded dead. The main bycatch species are whiting (*Merlangius merlangus*), haddock (*Melanogrammus aeglefinus*) and cod (*Gadus morhua*). Here we summarize the known behavioural reactions of these species towards conventional trawls and review the results of using different trawl modifications to increase selectivity of *Nephrops* trawls. The trawl modifications are categorised as separator grids, separator and guiding panels, square-mesh panels, capture avoidance designs and codend modification. Finally, the extent to which these developments have been legislated for is discussed including the conditions under which new gear regulations have been introduced.

Haddock and whiting rise during the trawling process facilitating their separation from *Nephrops* and escape, however the behaviour of small fish of these species is less consistent. Cod and *Nephrops* remain on bottom of the trawl, so to separate these species requires some physical filtering process. Overall, there is currently sufficient technical ability to improve selectivity in *Nephrops* trawls. The design of choice is dependent on the objectives of managers; for reducing discards but retaining marketable fish, square-mesh panels offer the most useful tool; to eliminate all bycatch and create a single-species fishery, grids and traditional *Nephrops* trawls show most potential. Whatever the objectives of the new measures, it is likely that a short-term economic impact will follow, and some form of incentive may be required to implement effective measures. A voluntary uptake of new measures by industry is preferable, however, to date, restrictions on fishing opportunities have been necessary to introduce innovative gear designs.

Keywords *Nephrops* · Trawl · Fish behaviour · Gear technology

Introduction

The northeast Atlantic *Nephrops norvegicus* trawl fishery have been ranked as having the fifth highest discard ratio (by number) in the world (Alverson et al. 1994). The *Nephrops* fishery is one of three types of trawl fishery in the North Sea responsible for most discarding (Anon. 1999). Trawlers targeting *Nephrops*, commonly known as langoustine, Dublin Bay prawn or scampi, use net mesh sizes smaller than that used to target whitefish. Furthermore, several important commercial whitefish species occur in the same areas that *Nephrops* inhabit, so there is a large

T. L. Catchpole (✉) · A. S. Revill
Centre for Environment Fisheries & Aquaculture Science (CEFAS), Pakefield Road, Lowestoft NR33 0HT, UK
e-mail: thomas.catchpole@cefas.co.uk

bycatch of whitefish in *Nephrops* trawl fisheries, much of which is undersized and is discarded dead. Bycatch refers to organisms, other than the target species, that are retained in the trawl, some of which are landed, the rest discarded.

Commercially the most important bycatch fish species are whiting (*Merlangius merlangus*), haddock (*Melanogrammus aeglefinus*) and cod (*Gadus morhua*). Whiting is recorded as the dominant species discarded in *Nephrops* trawl fisheries in the Irish Sea (Briggs 1991), North Sea (Evans et al. 1994; Redant and Polet 1994; Catchpole et al. 2005a), Celtic Sea (Rochet et al. 2002) and Clyde Sea (Bergmann et al. 2002). Haddock is also discarded in large quantities in the North Sea, Clyde Sea, Celtic Sea and Kattegat Sea *Nephrops* fisheries (Wieczorek et al. 1999; Rochet et al. 2002; ICES 2004; Catchpole et al. 2005a).

The catching of large numbers of undersized fish in the *Nephrops* trawl fisheries is not a recent problem, having been first highlighted 40 years ago, at which time whiting was still the most abundant bycatch species (Thomas 1965). Around this time it was also noted that different species react differently during the trawl capture process. For example, large numbers of whiting escaped through the top of the net before reaching the codend (Margetts 1963). It was reasoned that the composition of catches could be manipulated by altering the design of trawls.

These observations led to the first attempts to design trawls that would allow the escape of undersized whiting and other fish while retaining marketable *Nephrops*. One early example was a trawl devised by Symonds and Simpson (1971) with 70 mm meshes in the topsheet and 50 mm in the belly, and a codend divided by a horizontal sheet of netting. This design did show promise—79% of *Nephrops* were taken in the bottom codend, 62% of marketable whiting were taken in the top. However, despite these early developments, fishery managers and scientists still seek solutions to the continued high discard rates in *Nephrops* trawl fisheries.

Here we examine the progress made in improving species and size selection in *Nephrops* trawls in the North Sea, Irish Sea, Kattegat and Skaggerak. These are the areas where most research into *Nephrops* gear technology has been conducted; a similar range of species is caught, and similar problems relating to bycatch are found (Graham and Ferro 2004).

First, we summarize the behavioural reactions of the main species towards conventional trawls. Then, we review the results of experiments using different modifications. Much of this material has not been published in scientific journals and consists of internal and external reports from a variety of European research institutes. The different modifications are categorised as separator (or selection) grids, separator and guiding panels, square-mesh panels, capture avoidance designs, and codend modification. Finally, the extent to which these developments have been legislated for is discussed. Also, the conditions under which new gear regulations have come into effect are considered with the aim of determining the driving forces behind their implementation. Directions for future research on gear design are proposed, alongside the incentives necessary for their successful introduction.

Species behavioural reactions when encountering trawls

The trawl capture process is not a simple sieving process (Wardle 1983); fish are herded into the mouth of a trawl by the otter boards, sweeps, and bridles (and the sand or mud cloud they create), and remain swimming there until they become fatigued and drop back into the net. When they tire, different species react in predictable and different ways (Main and Sangster 1986).

Haddock, whiting and cod behaviour

Haddock rise high (up to 10 m) off the seabed before passing over the footrope into the net or escaping over the headline. Whiting enter the net at a height lower than haddock but higher than many groundfish species (e.g. cod, flatfish, monkfish, rays and dogfish) (Main and Sangster 1985b). They can swim strongly within the trawl extension and make repeated attempts at escape, especially when confronted with the narrow confines of the extension and codend. They have been observed moving slowly along the topsheet trying to push through the meshes. Generally, whiting face forwards and are overtaken by the trawl (Briggs 1992). Whiting have also been observed drifting facing the sidewalls of the net and making intermittent dashes at it (Briggs and Robertson 1993).

During the more limited observations on cod, no escape attempts have been observed. They drift slowly back along the extension, keeping station in the net for long periods (Briggs 1992; Briggs and Robertson 1993). However, there is evidence from gear trials that small cod may rise inside the trawl and escape if given the opportunity (Main and Sangster 1985a; Robertson and Stewart 1988; Thorsteinsson 1991; Ulmestrand and Larsson 1991; Madsen and Moth-Poulsen 1994; Dunlin and Reese 2003).

Once fish reach the codend and it begins to fill, the diamond-mesh netting used in the construction of most *Nephrops* trawls stretches into a bulbous shape (Robertson and Stewart 1988). In the codend, most fish escape from the open meshes at the front of this 'bulb'. Only a small proportion of the meshes in a diamond-mesh codend are open wide enough to allow fish to escape; these are found at the front and rear parts of the codend (Robertson and Stewart 1988).

The response of fish to trawls is modified by their ability to see, hear and react by locomotion (Kim and Wardle 2003). Most observations of fish behaviour within trawls were necessarily made during light conditions and behaviour may differ in dark conditions (e.g. Glass and Wardle 1989). *Nephrops* fishing occurs mostly during daylight, when *Nephrops* leave their burrows, however, disturbance of soft sediments by the trawl is likely to reduce light levels. More research is required to better understand fish behaviour during commercial trawling for *Nephrops*.

Nephrops behaviour

Nephrops inhabit burrows in sand/mud sediments. They react to disturbance by initiating tail-flips that propel them backwards. To be caught, *Nephrops* must be induced to swim up and over the groundgear (Main and Sangster 1985a; Newland 1989). Those in or near their burrows have been observed making rapid withdrawal into the burrow as the groundgear passes over them; those away from their burrows respond by tail-flipping (Newland 1989).

Some *Nephrops* have been observed swimming actively away from trawls, but, the herding efficiency of the sweeps, bridles and wings is low for *Nephrops*; instead these parts of the trawl tend to move under them and they avoid capture (Main and Sangster 1985a; Newland 1989). Most *Nephrops* swim only after physical contact with the groundgear. Swimming duration is short and at speeds in the region of 0.5 m s^{-1}, and because trawl towing speeds are faster ($\sim$1.3 m s^{-1} or 2.5 knots), *Nephrops* are quickly over-taken by the trawl (Newland 1989).

Once inside the trawl, *Nephrops* pass along the bottom of the net and seldom rise above the selvedges (Main and Sangster 1985a). The average swimming height rarely exceeds 0.5 m (maximum 1 m) (Briggs and Robertson 1993). *Nephrops* within the net drift passively along the middle of the lower sheet, tumbling with no apparent control (Briggs and Robertson 1993).

Nephrops can, however, escape from all parts of the trawl and the length frequency of released *Nephrops* can be dependent on the part of the trawl from which they escape (Cole and Simpson 1965; Hillis and Earley 1982). *Nephrops* selection has a shallow ogive giving a wide selection range (SR). This is attributable to the general morphology of the species—the many appendages get caught in the meshes and other organisms in the trawl, causing the retention of even small individuals (Briggs 1986).

Selective *Nephrops* trawl designs

There have been many gear trials using many different *Nephrops* trawl designs. Owing to the different methods and materials used, the areas fished, the between-trial variation in the catch composition, the species size frequencies of the fish encountered, and the environmental conditions, it is not possible to make direct comparisons between trials. Therefore, what we present here is a review of the work conducted and the findings generated for which there is some consensus.

Selection grids

The use of grids to improve trawl selection depends little on the behavioural reactions of species, but instead relies more on physical filtering the catch (e.g. Robertson and Shanks 1997). The grid designs tested in *Nephrops* fisheries generally work by allowing those animals small enough to pass through a row of vertical bars to move into the codend, while those that are too large are guided to their escape (Fig. 1). Consequently, large fish are expelled from the trawl, whereas the smallest fish can still be retained. Most of the recent work with grids has been done in the Swedish *Nephrops* fishery, during which a grid with bar spacing of 35 mm and a 70 mm diamond mesh codend significantly reduced the bycatch of fish when compared with a standard 70 mm diamond-mesh trawl. The trawl with the grid reduced the catch of commercially sized fish (whiting, haddock and cod) by 80–100% and undersized fish by 30–65% (by weight) (Ulmestrand and Valentinsson 2003).

Trawls with the same basic specifications as those used in Sweden were also compared in the North Sea Farn Deeps fishery. The grid trawl significantly reduced marketable cod, haddock and whiting by 70–100% (by number). The number of undersized whiting was significantly reduced, but no change was detected for haddock, and the numbers of undersized cod increased by 114% (Catchpole et al. 2006b).

The increase of capture of small cod with the grid has been attributed to the reduced selectivity in the codend caused by a reduction in the quantity of fish retained. Codends containing more roundfish tend to float higher and the meshes to remain more open than when the catch consists mostly of *Nephrops* and flatfish (Galbraith 1991). Increased catches of *Nephrops* have also been associated with reduced roundfish catches caused by reduced codend selectivity (Dunlin and Reese 2003; Valentinsson and Ulmestrand 2005).

Also in Sweden, grids have been tested to reduce the SR of retained *Nephrops.* The minimum landing size (MLS) of *Nephrops* in the Kattegat and Skagerrak regions is 40 mm carapace length (CL) (compared with 25 mm CL in most of Europe). This leads to large scale discarding of small *Nephrops* in these fisheries. Several designs have shown that grids retain *Nephrops* with a smaller SR than diamond-mesh codends (Valdermarsen et al. 1996; Valdemarsen 1997).

Criticisms of the grids by the industry include handling difficulties and blocking. Recent trials have begun to investigate flexible grids, which are lighter and fit more easily around net drums (Loaec et al. 2006).

Separator and guiding panels

To utilize species behavioural reactions in trawls, horizontal separator panels have been inserted inside the net (Main and Sangster 1982). These are designed to separate whiting and haddock from *Nephrops* and groundfish. The separator panel is inserted at an appropriate height inside the trawl which terminates in two independent codends with different mesh size; a larger mesh size for the upper codend, retaining whiting and haddock, and a smaller mesh size for the lower codend, retaining *Nephrops* and other fish.

Early designs showed good levels of separation (Main and Sangster 1982; Ashcroft 1983). In the South Minch fishery, the optimum set-up was a

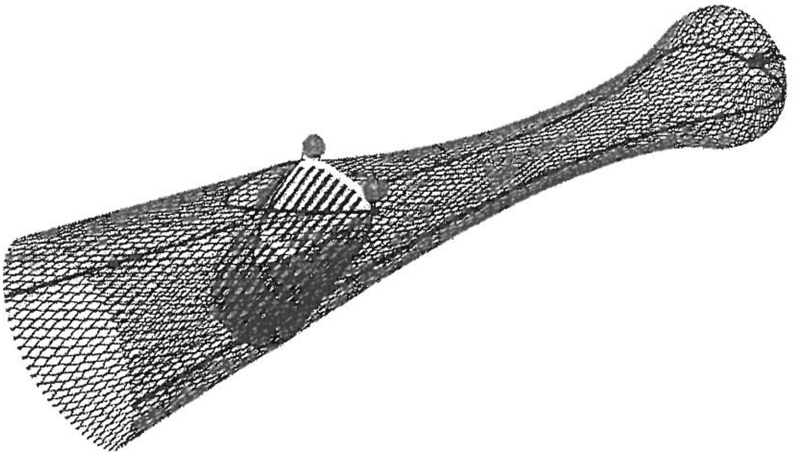


Fig. 1 *Nephrops* trawl with grid (Copyright 2004 reproduced with permission of FRS, Aberdeen)

50 mm mesh separator panel positioned 75 cm above the bottom sheet. With this configuration, 94% of whiting and 96% of haddock were separated from 99% of *Nephrops* and 100% of cod (Main and Sangster 1982). Further trials have continued to demonstrate an effective separation of *Nephrops*, but when encountering larger numbers of whiting and haddock the level of separation is reduced (Hillis 1989; Sangster et al. 1990; Dunlin 1999).

In the North Minch fishery, with the panel at a height of 90 cm above the footrope, 67% of haddock and 49% of whiting were retained in the upper codend (90 mm). In those trials, almost all whiting (87%) and haddock (82%) in the lower codend were below MLS (27 and 30 cm, respectively) (Sangster et al. 1990). This suggests that separation is less for smaller length classes of whiting and haddock, an observation reported from other gear trials too (Hillis 1984, 1985). Using a 90 mm upper and 70 mm lower codend, plus a horizontal panel set 75 cm above the footrope, larger quantities of discard sized whiting, haddock and hake (*Merluccius merluccius*) were taken in the lower codend, with only the largest whiting more numerous in the upper codend (Galbraith 1991). In trials conducted in the Irish Sea, separation was poor for fish <20 cm (Dunlin 1999).

Various lengths of separator panel have been investigated, from a full panel (extending the length of the trawl to the codend) to no panel (simply, two separate codends). Results from all designs have been similar, with percentage separation rates of *Nephrops* and whiting at >75%. A modified separator design devised by Hillis (1983) used a screen of large mesh fitted at an angle over the mouth of the lower codend to increase the herding effect of fish into the upper codend. This separated 83–90% of whiting of all length classes into the top codend.

Attempts to separate cod into a top codend have also been made. Hillis (1989) had limited success with guiding ropes stretching diagonally from the separator panel to the floor of the trawl. The same method was used by Sangster et al. (2003) and most cod, haddock and whiting were separated from *Nephrops* and flatfish.

Separator trawls have also been used in conjunction with grids. Radcliffe (2001) used a two-tier codend with two grids, the first to sort fish from *Nephrops*, and the second to sort *Nephrops* by size, allowing the smallest to escape. Fish separation was high but there was a loss of ~20% of the legal-sized *Nephrops* catch. Similarly, Graham and Fryer (2006) trialled a two-tier codend with one grid to separate *Nephrops* from fish in the lower codend (bar spacing 25 and 30 mm). The level of separation was high for fish over >20 cm and for *Nephrops* with CL < 50 mm.

So far, fishers have not adopted separator trawls, criticising the initial expense and complication of fitting and using the extra codends. The most recent work has focused on guiding panels. These work using the same principle as separator panels, but once separated, the fish are guided to either an escape hole or to a square-mesh panel (see below) instead of a second codend. Guiding panels are generally shorter than separator panels, are situated at the end of the tapered section, and are set at an incline.

The Inclined Separator Panel is one such design, and it was developed to facilitate the release of cod from *Nephrops* trawls in the Irish Sea (Fig. 2). The separator panel is fitted into the trawl at an angle of 30°, starting 30 cm above the bottom sheet, to divert cod and other whitefish upwards towards an escape hole on the topsheet. Initial results demonstrated release rates of 68% for whiting, 98% for haddock and 68% for cod (Rihan and McDonnell 2003). Further trials have produced release rates of up to 91% for whiting and 77% for cod, but a significant loss of *Nephrops*, ~35%, has also been observed (BIM 2005a, b, c).

In an attempt to retain marketable fish and increase the probability that undersized fish encounter a square-mesh panel (SMP), trials of a combination of a guiding panel and a SMP were conducted in a Portuguese crustacean fishery (Campos et al. 1996). This was followed by preliminary trials in the South Minch *Nephrops* fishery, a trawl with an 80 mm codend, 100 mm SMP and a guiding panel caught significantly fewer whiting <30 cm relative to a trawl with no guiding panel (R. Kynoch unpublished).

Square-mesh panels (SMPs)

When conventional (diamond mesh) netting is rigged to hang with the bars parallel and perpendicular to the tow direction, the meshes adopt a square shape.

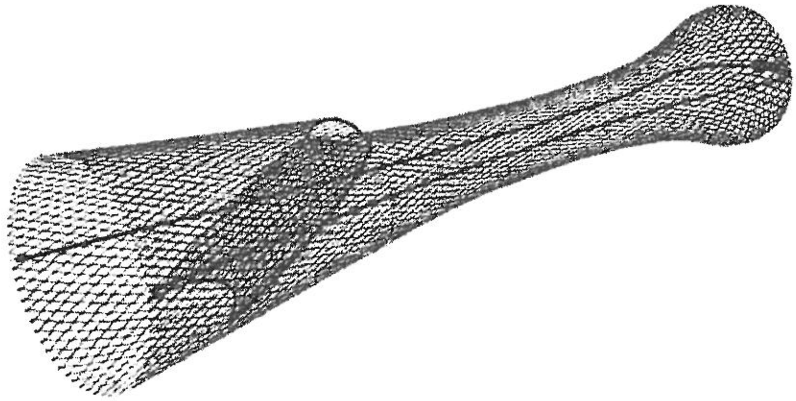


Fig. 2 Inclined separator panel (Copyright 2004 reproduced with permission of FRS, Aberdeen)

Experiments have shown that these square meshes remain more open than conventional diamond meshes during trawling, so facilitating the escape of fish (Robertson and Stewart 1988).

Moreover, the inclusion of a square-mesh panel in the net (Fig. 3) alters the physical conditions within the trawl in a way that encourages an escape response from several fish species. Observations indicate that fish respond actively to a sudden change in water flow and light conditions, as experienced by fish when they pass from diamond to square-mesh sections of netting (Arkley 1990). In comparative trials, few escapes were observed through a 150 mm diamond-mesh panel in a 70 mm trawl, whereas there were frequent escapes of whiting through an 80 mm SMP (Briggs and Robertson 1993).

There has been a myriad of experiments using SMPs (or windows) in *Nephrops* trawls. Panels of different size, mesh size, constructed of various materials have been inserted in a variety of positions in the top of the trawl, principally to encourage the escape of whiting and haddock. Typically, insertion of a panel reduces the level of retention of whiting and haddock (Arkley 1990; Hillis et al. 1991; Thorsteinsson 1991; Ulmestrand and Larsson 1991; Madsen and Moth-Poulsen 1994; Robertson and Shanks 1994b; Madsen et al. 1999), and the panels do not release *Nephrops* (Arkley 1990, 1993; FRS 2002).

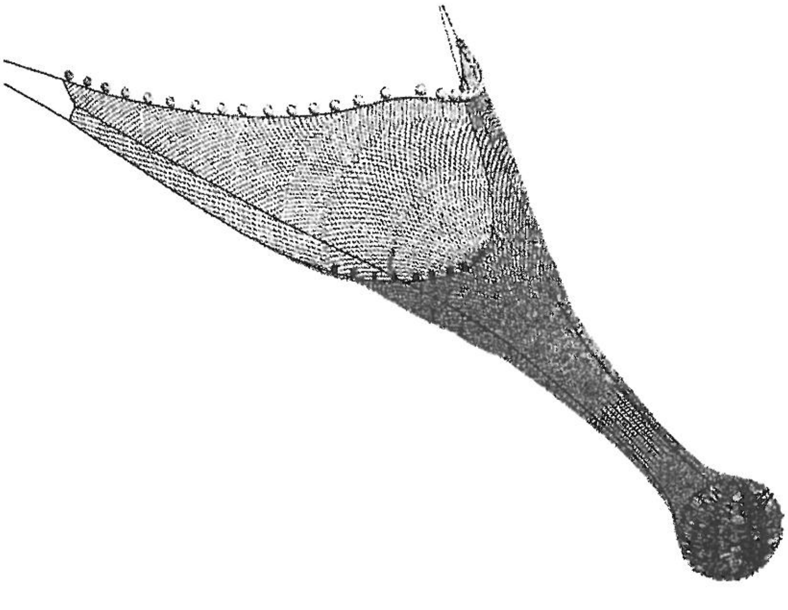


Fig. 3 Square-mesh panel inserted in a diamond mesh codend (Copyright 2004 reproduced with permission of FRS, Aberdeen)

Size selection in SMPs

There is no clear size selection pattern by SMPs. Trials have demonstrated either a greater escape of fish larger than the MLS than below the MLS (Madsen and Moth-Poulsen 1994; Polet and Redant 1994); an escape of more fish smaller than the MLS (Arkley 1990; Armstrong et al. 1998; FRS 2002); or a reduction in fish across their length range when using an SMP (Ulmestrand and Larsson 1991; Briggs 1992). There is no evidence that *Nephrops* escape from square-mesh panels during trawling when the panels are positioned in the topsheet.

Underwater observations have shown that escape through the panel is given by an active response from the fish (Briggs 1992; Briggs and Robertson 1993). Swimming performance, and possibly visual acuity (Douglas and Hawryshyn 1990), likely increase with size and so larger fish have a better chance to escape (Madsen et al. 1999). Furthermore, smaller individuals may stick together in schools, while larger fish behave as individuals (Madsen and Moth-Poulsen 1994). This could result in less predictable behaviour of smaller size classes, which would correspond with the findings from SMP and separator panel experiments.

SMP position

In general, the closer to the codend the SMP is inserted, the higher the rate of escape of whiting and haddock in *Nephrops* trawls (Hillis et al. 1991; Arkley 1993; Briggs and Robertson 1993; Robertson and Shanks 1994a; FRS 2002). In the Fladen area, a 90 mm SMP positioned 9–12 m from the codline was more effective at reducing haddock and whiting than a SMP 15–18 m from the codline (FRS 2002).

In the Irish Sea, (Hillis et al. 1991) three positions for a 70 mm SMP were assessed. A reduction of 35% undersized and 20% marketable whiting was achieved with the SMP in the topsheet; a reduction in 41% undersized and 31% marketable whiting with a 4 m panel forward of the codend; and a reduction of 86% undersized and 49% marketable whiting with the 7 m panel in the full length of the extension and codend.

The areas of greatest escape rate are in the extension and the codend, where the fish become more channelled and concentrated, increasing the probability of fish encountering an escape opening (Arkley 2001). The overall length of the extension can also influence SMP effectiveness. With no increase in SMP length, excessive extension lengths can reduce panel performance owing to the exhaustion of fish, particularly juveniles (Arkley 2001). The exhaustion of fish and overcrowding in the extension and codend were reasons given to explain why more undersized whiting escaped from a SMP 7 m in front of the extension than from a SMP inserted just 1 m in front of the extension (Armstrong et al. 1998).

The pattern of increased escapements from the panel when it is inserted near the codend is supported by the findings of a trial using two SMPs. In addition to a SMP at 9–12 m from the codline, Revill et al. (2006a) inserted a second panel at two positions, 20.6–23.6 and 24.5–27.5 m from the codline. The former of the two, the one closest to the codend, convincingly outperformed the other, reducing catches of cod, haddock and whiting <MLS by ~50% relative to a single SMP at the 9–12 m position.

SMP length

In *Nephrops* trawls, panels of 2–7 m have been tested. Whiting and haddock tend to escape on the first attempt, mostly through the first few rows of the panel (Briggs 1992; FRS 2002). Furthermore, prolonged exposure to square mesh netting as the fish move through the trawl, may result in the fish becoming acclimatised to the panel, lessening the escape response (Arkley 2001). Consequently, multiple SMPs may increase the number of escape responses and, as such, be more effective than single panels, as shown by Revill et al. (2006a).

Square-mesh and diamond-mesh netting have different geometric properties, so care must be taken to ensure that, when combining the two, it does not distort the shape of the trawl itself. Fishers have commented on the changes in the shape of trawls when inserting areas of square mesh netting; large areas of square mesh might, therefore, be impractical for some trawls.

SMP twine and mesh size

The materials used in the construction of SMPs can influence selectivity. One problem associated with a SMP is that the panels can distort as the material is stretched, reducing its effectiveness. The use of high strength, low diameter twine improves the selectivity for whiting and haddock (Revill et al. 2006a). A reduction of 55% and 79% of whiting and haddock <MLS was observed when using 2.5 mm twine compared with 4 mm twine in the same size panel (Arkley and Dunlin 2002).

Work in the Moray Firth compared small diameter twine in a SMP (5 mm and knotless 2.5 mm) with 5 mm double-knotted twine, as commonly found in commercial trawls. The small diameter twine reduced the catch of haddock considerably when compared with the 5 mm double-knotted twine. These trials highlighted the unsuitability of double-knotted twine for the construction of SMPs (FRS 2002).

Increasing the mesh size of the SMP has the same effect as decreasing the twine thickness. Early experiments used SMPs of mesh size 70–80 mm. Using a 70 mm mesh, 4 mm twine SMP, the mean length of whiting enmeshed in the panel was 26 cm (Hillis et al. 1991). This corresponded well with the MLS. However, this mesh size was less effective for haddock, owing to the different shape and larger MLS for this species. Recent trials in *Nephrops* fisheries have used SMP panels of mesh sizes up to 100 mm (R. Kynoch unpublished) and 120 mm (Norman Graham, pers. comm.) to increase the escape of undersized haddock and also cod.

The colour of twine also influences the effectiveness of SMPs (Revill et al. 2006a). The visibility of twine varies according to its diameter, colour, and angle relative to the water surface. Observations of fish have shown that behavioural patterns are explained primarily by a visual response to the gear (Glass and Wardle 1989), fish generally avoiding netting that is visible and instead choosing a route perceived to be less hazardous (Glass et al. 1993, 1995; Jones et al. 2004). However, the relative importance of the size, position, twine colour, and twine diameter of SMPs is at present unknown.

Capture-avoidance designs

The aim of such trawls is to avoid the initial capture of unwanted fish rather than to improve their chances of escape from the trawl. Capture-avoidance designs are based on trawl designs previously used to target *Nephrops* in single-species fisheries (known as prawn or *Nephrops* trawls) (SFIA 1985). However, in the last 20 years, vessels have moved away from using these designs to using dual-purpose 'fish/prawn' trawls to capitalise on the marketable fraction of the fish bycatch. Prawn trawls have no sweeps and bridles, so no fish are herded towards the trawl, and a low headline (<2 m) with no cover (Graham and Ferro 2004), so even those whiting and haddock encountering the trawl escape over the headline. These are still used in some inshore fisheries as they enable access to areas in which it is not possible to manoeuvre larger trawls.

Trials with a contemporary prawn trawl or 'cutaway' design have been conducted in Mallaig, Farn Deeps and Clyde areas (Fig. 4). A conventional 'fish/prawn' trawl was altered by reducing the headline height, shortening the wing length, removing the cover, and increasing the mesh size in the upper panels of the net (FRS 2002; A. Revill et al. unpublished). The trials demonstrated a considerable reduction in the numbers of haddock and whiting retained across the full size range, reduced cod catches by 11% (mostly in size range 15–30 cm) and increased *Nephrops* catches by 20% (Dunlin and Reese 2003). The cutaway trawl reduced discarding of whiting in the Farn Deeps fishery by around 50%, but, only in proportion with the landings (Revill et al. 2006b). The loss of marketable fish dissuaded fishers from adopting this design.

Codend modification

Codend effects on *Nephrops*

Some gear trials comparing different diamond-net mesh sizes have demonstrated that an increase in mesh size does not generally affect the SR for *Nephrops*, but can reduce retention across the length range. Consequently, there is little difference in the catch composition, only in catch numbers. Robertson and Ferro (1993) showed that the *Nephrops* selection ogives from 70 and 80 mm diamond-mesh trawls provided similar *Nephrops* L_{50}, but with the 80 mm diamond-mesh, the *Nephrops* catch was reduced by up to 34%.

More recent studies indicate that most *Nephrops* encountered by trawls are caught using codends of mesh sizes up to 90 mm. A 16 mm diamond-mesh

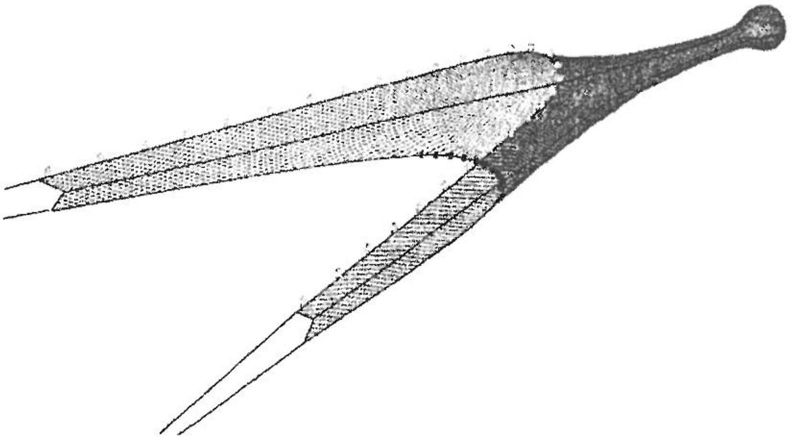


Fig. 4 Cutaway trawl with set back headline (Copyright 2004 reproduced with permission of FRS, Aberdeen)

codend has the same selection properties as a 70 mm diamond-mesh codend (M. Ulmestrand and J. W. Valdemarsen unpublished); an 80 mm diamond codend was no more selective than a 70 mm diamond codend (Catchpole et al. 2005a); and no difference was identified in *Nephrops* catches between an 80 mm and a 90 mm diamond-mesh codend (FRS 2002).

Above 90 mm mesh size, *Nephrops* can escape from a trawl and the selection is size-dependent. In the Farn Deeps fishery, 43% fewer *Nephrops* in the smaller size range ('tails'; ~<30 mm CL) and 34% fewer larger *Nephrops* were caught with a 120 mm diamond-mesh codend than with a 70 mm diamond-mesh codend (Andrew Revill, pers. comm.). Similarly, there was a reduction of 70% in *Nephrops* measuring 20–25 mm (CL) and 36% in *Nephrops* measuring 25–30 mm (CL) using a 100 mm mesh codend (5 mm double twine) compared with a 70 mm codend (4 mm single twine) (FRS 2002).

As with SMPs, the twine used in the codend influences the selection properties of trawls on *Nephrops*, whereby the use of thicker and more rigid twine or multiple twine reduces the selective properties of the codend (Polet and Redant 1994; Briggs et al. 1999). For example, an 80 mm diamond-mesh codend of 6 mm twine caught 34% more *Nephrops* than one of 3.5 mm twine (Anon. 2000).

There is evidence of an increase in *Nephrops* L_{50} but with similar selection ranges when using square-mesh codends compared with diamond-mesh (Robertson et al. 1986; Robertson and Shanks 1989; Larsvik and Ulmestrand 1992). This suggests square-mesh codends catch the same size range of *Nephrops* but fewer small *Nephrops* than diamond-mesh of the same mesh size. When comparing a 60 mm square-mesh codend with a 70 mm diamond-mesh codend, there was a loss in *Nephrops* of CL <45 mm (Larsvik and Ulmestrand 1992; M. Ulmestrand and J. W. Valdemarsen unpublished); *Nephrops* L_{50} was higher by up to 14 mm CL (Larsvik and Ulmestrand 1992).

Codend effects on whiting, haddock, and cod

The catches of whiting, haddock, and cod are also less with the square-mesh codends (Robertsen 1983; M. Ulmestrand and J. W. Valdemarsen unpublished) compared with diamond-mesh codends of the same mesh size. Square-mesh codends have a greater L_{50} for haddock and whiting than diamond-mesh codends of the same mesh size. Square-mesh codends can also produce sharper selectivity and so retain fewer undersized fish than a diamond-mesh codend with the same L_{50} (Robertson and Stewart 1988). This is likely because meshes in square-mesh codends remain uniformly open as the codend fills (Robertson and Stewart 1988).

When the mesh size of diamond-mesh codends is increased, an improvement in selectivity for both whiting and haddock can usually be demonstrated. A significant reduction in catch rate of small whiting was seen with a mesh size increase from 70 to 80 mm (Briggs et al. 1999). A reduction in haddock discards of 47% was demonstrated with an increase in codend diamond-mesh size from 110 to 120 mm; however, there were also reductions in numbers of marketable fish (FRS 2000).

In non-*Nephrops* fisheries, the selectivity of diamond-mesh codends towards roundfish is reduced by increasing the number of meshes in the codend circumference, and by attaching lifting bags (Broadhurst and Kennelly 1996; FRS 2000), factors that will likely also affect *Nephrops* trawls.

Management implications

Details on the current legislation in all the *Nephrops* fisheries in the study area are given in ICES (2003) and Graham and Ferro (2004). The minimum legal mesh size for *Nephrops* trawls in the North Sea and Irish Sea is between 70–95 mm diamond mesh. There is also national and EU legislation for the requirement of diamond and square-mesh panels, the size, mesh size and position of those panels, and the permissible twine thickness and circumference of the codend. However, despite these measures, *Nephrops* fisheries in these areas still generate substantial quantities of discards (ICES 2003).

In Swedish national waters, it has been mandatory to use a grid when trawling for *Nephrops* since 2004. The grid has a bar spacing of 35 mm, and is combined with a 70 mm square-mesh codend that facilitates the escape of small fish. The loss of *Nephrops* smaller than the MLS (40 mm CL), a consequence of using this codend, has likely had no significant economic impact in this fishery, but would do so elsewhere (MLS 25 mm CL). The fishery is now a single-species fishery—in 2004, *Nephrops* constituted 94% of the landings (Valentinsson and Ulmestrand 2005).

Several of the stocks of species that are taken as bycatch in *Nephrops* fisheries are currently classified as overexploited. Stock recovery programmes and other measures to improve stocks are in place for whiting and hake in the Irish Sea, and for cod in the Irish Sea, West of Scotland, North Sea and Skaggerak and Kattegat regions. As part of a series of technical measures to improve the Irish Sea cod stock, the use of an Inclined Separator Trawl, which was implemented to reduce the capture of cod but also reduces whiting and haddock catches, is mandatory for *Nephrops* vessels working in an otherwise closed area of the Irish Sea (Rihan and McDonnell 2003).

There are no reports of widespread voluntary uptake of new selective gear designs by the industry. There are, however, a number of examples of individual fishermen who have made alterations to their gear or adopted gear designs used in trials on their vessels. In general, the principal impediment to introducing new gear measures is the negative economic effect expected by industry. Species and size selection is not an exact process, and some marketable catch will often be lost as a consequence of introducing more selective gear. Gear trials have shown that it is possible to reduce the bycatch of fish, in particular whiting and haddock, but at the expense of losing some of the marketable fish and/or marketable *Nephrops*.

Increasing codend mesh size or using square-mesh codends is an effective way to select out unwanted fish bycatch, but it also releases large numbers of marketable *Nephrops* (and some marketable fish). Utilizing the behaviour of whiting and haddock has meant that large numbers can either be separated into an upper codend, enticed escape through a SMP, or to avoid capture by the trawl. However, the behaviour of smaller fish appears less consistent than larger fish, and levels of separation/escapement for small fish can be lower.

Selectivity trials and data from fine-mesh trawls indicate that large numbers of small fish do already escape from *Nephrops* trawls currently used by commercial vessels (Catchpole et al. 2006a). However, with a growing awareness of the impact that discarding has on commercial stocks and on the wider ecosystem (Cook 2001; Catchpole et al. 2005b), reducing the catch of unwanted fish remains an important management objective. The task for gear technologists is to develop the means to further reduce unwanted catches while also retaining as much of the marketable catch as possible. Moreover, with some stocks currently categorised as being fished unsustainably, there is also a need to develop trawls that do not catch overexploited species at all.

This highlights the need for specific and defined management objectives. For example, measures designed to minimize all cod catches would be quite different from those required to reduce the capture of unmarketable whiting and haddock. In some instances, the objectives for new gear regulations have been unclear and consequently ineffective. The threat of severe fishing restrictions in the Farn Deeps fishery, owing to the poor status of the cod stock, in conjunction with the new regulations imposed on other fisheries, provided the necessary incentive to implement new gear regulations in 2002. The regulations included inserting a large diamond-mesh panel near the headline, increasing the codend mesh size from 70 to 80 mm and increasing the size of the SMP from 80 to 90 mm. These measures are likely to reduce the capture of small haddock and whiting (Catchpole et al. 2005a), but will likely produce less benefit for cod.

The new regulations introduced in the Farn Deep fishery did, however, allow the fishery to continue without further restrictions on fishing (Catchpole 2005; Catchpole et al. 2005a). Unlike the Farn Deeps fishery, fishing restrictions were already in place in the Irish Sea and Kattegat/Skaggerak region before new and much more substantive gear regulations were introduced. National legislation meant that Swedish waters were closed to all trawling without the use of a grid. This was followed by EU legislation that introduced the grid for use outside Swedish waters in the Skagerrak/Kattegat region. Currently, fishing effort is restricted to 21 days per month for fishermen who use grids, and 9–11 days for those who do not (Revill 2005). Similarly, only when using the Inclined Separator Trawl are fishermen allowed access to an otherwise closed area in the Irish Sea (Rihan and McDonnell 2003).

The economic importance of the fish bycatch in *Nephrops* fisheries is highly variable. In the Fladen fishery, fish bycatch can contribute up to 60% of total income (Graham and Ferro 2004). In the inshore fisheries around the Hebrides, fishers focus on *Nephrops* using traditional low-headline nets, and the importance of the fish bycatch is limited (Graham and Ferro 2004). Consequently, the economic impact of introducing new gear designs and the level of incentive required to introduce new gear will be fishery-dependent. Those fisheries that would profit from improved fish stocks may require less incentive if it can be demonstrated that new gear designs will benefit the stocks.

Economic incentives are clearly a powerful tool in introducing new gear regulations, but these must be balanced with introducing gear designs that will minimise any loss in income. Not only will this aid the implementation process, but it will increase industry support and lessen any circumvention of new regulations. Even with full compliance with new legislation, fishermen must be proactive in rigging their gear to make new measures effective.

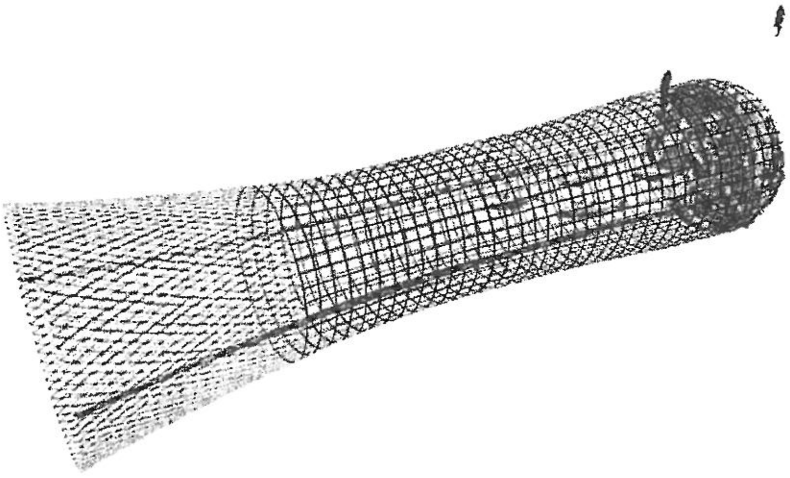
An enhanced understanding of the ecological and economic benefits of reducing discards will provide incentive to both industry and managers alike. There has been no comprehensive study on the biological and economic benefit of introducing new *Nephrops* trawl designs. In conjunction with the need to promote more selective fishing methods within the industry is the need to strengthen the motivation of managers. An example of the outcome of enhancing political will is provided by Sweden. The Swedish Social Democrat Government were dependent on the Green Party to achieve a majority in Parliament. It was only through this collaboration that the necessary political desire was generated to initiate a ban on trawling for fish in national waters and in turn to implement the grid and square-mesh codend *Nephrops* trawl (Fig. 5).

Conclusion

The different behaviours exhibited by the main bycatch species in *Nephrops* trawl fisheries can be exploited to improve the selectivity of trawls. Whiting and haddock rise when inside the trawl, while *Nephrops* and cod remain near the bottom. Separating cod, and other groundfish, from *Nephrops* remains the most challenging task for gear technologists in this fishery. However, this review illustrates that there is currently adequate technical ability to significantly improve the selectivity of *Nephrops* trawls.

If the aim of fishery managers is to retain as much of the marketable bycatch as possible but to reduce discards, then designs involving SMPs, constructed of large mesh, high-strength thin twine, possibly in combination with guiding panels/funnels/ropes should be further developed. Some loss of marketable fish will be likely using these designs, mostly whiting and haddock, but the catch of unwanted fish will be reduced. Being less complex and expensive than other designs, the use of SMPs is also the most supported technical measure by skippers of *Nephrops* trawlers (Catchpole 2005).

Fig. 5 Square mesh codend (Copyright 2004 reproduced with permission of FRS, Aberdeen)



If, however, the aim of managers is to minimise all fish bycatch or the bycatch of a particular overexploited species, such as cod, then a move towards a single-species fishery is more appropriate. A grid system or the prawn trawls historically used, offer promising solutions in this instance. In *Nephrops* fisheries where substantial quantities of both *Nephrops* and fish are landed, this may lead to separate fish and *Nephrops* fisheries in the same area, which could facilitate the management of the various commercial species. A greater understanding of fish behaviour towards different parts of the trawl would assist in the development of these designs and may also prompt research of innovative trawl modifications not yet considered.

Whatever the objectives of the new measures, it is likely that a short-term economic impact will follow, and some form of incentive may be required to implement effective measures. If fishers cannot be convinced of the medium and long-term conservation and economic benefits of more selective fishing, and be persuaded to voluntarily adopt new measures, then direct economic incentives will be required. It is important to note that many of the advances described here were achieved through the close collaboration of scientists and fishers during gear trials on commercial vessels. An improved understanding of the benefits of reducing the capture of unwanted fish and continued close collaboration with fishers when developing new trawl designs would enhance the possibility of a voluntary uptake of new measures. However, to date, restrictions on fishing opportunities have usually been necessary to introduce innovative and successful gear designs.

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