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A REVIEW OF POTENTIAL TECHNIQUES TO REDUCE THE ENVIRONMENTAL IMPACT OF DEMERSAL TRAWLS

by

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OVERVIEW OF THE PHYSICAL AND BIOLOGICAL EFFECTS OF BOTTOM TRAWLING

1.1 Introduction

Concern over the possible effects of trawls on the seabed has existed almost as long as the fishing method itself, with early concerns being voiced by fishermen themselves as far back as the 14th century (Graham, 1955; Lindeboom and de Groot, 1998). With the advance in technological developments of trawling gears (i.e. weight and size), particularly over the latter part of this century, the increase in the number of fishing vessels, engine power etc., these concerns are increasingly gaining international public and political importance.

This international concern was voiced at the 58th Council meeting in Copenhagen in 1970, at the International Council for the Exploration of the Sea (ICES). Information was requested with regard to the possible impacts of trawls and dredges on the seabed and on the benthic fauna (Lindeboom and de Groot, 1998). Following an initial flurry of activity, member states reported on these effects (Anon, 1973). There then followed a drop off in interest until the middle of the 1980's. In 1988, the ICES Study Group on the Effects of Bottom Trawling was convened in response to Council Resolution 1987/2:7 (Anon., 1988) to collect information available since 1972 and to report on the developments in bottom trawling gear, existing literature, national research and proposals for co-ordinated research (Anon., 1988). Their main conclusion related to the fact that the heavier gears now in use, in the North Sea in particular, might have a greater impact on benthic communities (Anon., 1988). New observations on the possible effects of these gears on the seabed were therefore required.

This led to renewed research interest with several countries undertaking systematic national studies (*e.g*. The Netherlands) into the direct effects of fishing activities on the benthos (Bergman *et al*., 1990; Bergman and Hup, 1992). Following on from these, multi-national studies were undertaken (IMPACT I and IMPACT II) which underlined the development in activities of the fishing industry within the participating states, but which also pinpointed a number of direct and indirect effects of trawling on the marine environment (see de Groot and Lindeboom, 1994; Lindeboom and de Groot, 1998). Pursuant on these projects, it is therefore clear that practical methods of reducing the identified effects on the benthos have to be found. This report aims to provide a broad overview of the effects of bottom trawling on the marine benthic ecosystem, with a view to identifying alternative techniques which may potentially help to reduce this impact.

Direct contact of trawling gear with the substratum via ground rope, chains, bobbins, sweeps, doors, chaffing mats or parts of the net bag may result in scraping, ploughing or sediment re-suspension (Jones, 1992). The ICES Study Group on The Effects of Bottom Trawling reported in 1998 on the state of the art (Anon., 1988). The effects on the bottom were classified as: scraping, penetration, pressure, sediment suspension, habitat destruction, burying, mortality in benthos (i.e. by removal of non-target invertebrates and damage and exposure of benthos in the trawl path).

1.2. Physical effects of trawling gears on the seabed

1.2.1 Penetration depth

Detailed systematic research on the physical impacts of trawling on the seabed, such as the depth of gear penetration, has been conducted since 1970. This followed the request from the International Council for the Exploration of the Sea for more information on the effects of trawls and dredges on the sea bed (Anon., 1973: Council Resolution 1970/S/1). The early studies tended to concentrate on the comparatively lighter beam trawls in use at the time but a few studies were also done for otter trawls (e.g. Bridger, 1970). Almost all beam trawls in the experiments were equipped with tickler chains with a single study involving a beam trawl equipped with a chain matrix (de Clerck and Hovart, 1972). Occasionally, both otter and beam trawls were investigated in experimental surveys (e.g. Houghton *et al*., 1971).

Penetration of bottom gear has been studied in different ways. Direct observations has been made by divers (e.g. Bridger, 1970; Margetts and Bridger, 1971) and submersible equipment such as underwater television cameras (Margetts and Bridger, 1971; Caddy, 1973; Sydow, 1990), side-scan sonar (de Groot, 1972; Khandriche *et al*., 1986; Krost *et al*., 1990; Sydow, 1990; Fonteyne *et al*., 1998), sediment profile imaging (Fonteyne *et al*., 1998) and seabed classification systems (Fonteyne *et al*., 1998). Bridger (1972) implanted markers into the sea bed and determined which part had been touched by the tickler chains of a beam trawl passing over them. Other researchers estimated the penetration depth from the benthos species caught by the gear (Houghton *et al*., 1971; Bergman and Hup, 1992) while Laban and Lindeboom (1991) measured changes in sedimentary characteristics before and after fishing.

It is important to note that further technological developments especially in the beam trawl fishery (i.e. greater beam lengths and weights, greater engine power etc.) since the early 1970's, have indicated the necessity for further study. Indeed, the physical mechanisms of seabed penetration resulting from the use of these heavier gears are currently the object of detailed study under the E.U. study "Trawl Penetration in the Seabed" TRAPESE (96/006). Laboratory experiments are currently being carried out on gear components moved over simulated sea bed in a towing basin at the Rostock University, whilst the forces and sediment displacement are measured and filmed. It is expected that more detailed information from this study will become available shortly.

While the direct physical mechanisms of gear penetration are not well understood, there is broad agreement among existing studies that gear penetration depth depends on:

- Gear type and number and weight of components
- Towing speed and warp length paid out
- Nature of the substratum(e.g. sand, mud, soft ground).
- Tidal conditions

1.2.1.1 Otter trawl studies

Bridger (1970) presented a thorough study on the effect of otter trawling on the seabed. The net used was relatively light in comparison with modern types consisting of a "Fleetwood 8 fathom" otter trawl with a groundrope length of 14.6 m and a headline length of 12.5 m. It was similar to those used by 100-120 hp vessels fishing in the vicinity of the experimental area (English Channel). The upper legs (bridles) between the doors and the wing-ends were 7.9 m and the lower legs 7.3 m long. The net was rigged with flat wooden doors of 1.5 m x 0.8 m. A variety of tickler chains ranging from 6-17 mm in diameter were rigged, either between the doors or between the wing-ends. Qualitative observations of the action of gear components on the seabed were made by divers. The trawl track was also investigated after passage of the gear. The towing speeds were low, c. 1.4 kn.

The tickler chains were seen to affect only a thin layer of top sand, although protruding or irregularly shaped boulders were regularly pulled out of the sediment. These dislodged stones were often carried along for a short distance before being deposited. The overturned boulders tended to make the trawl tracks more visible. An effect on the bottom was also observed for the lower bridles.

Caddy (1973) found trawl tracks caused by otter boards were a few centimetres in depth on sandy sediments in Chaleur Bay, Canada. Rumohr (quoted in Krost et al., (1990)), with the help of underwater video and SCUBA diver examination, recorded penetration depths of commercial otter trawls in Kiel Bay of 8-17 cm in mud and 0-5 cm in sand. Also in Kiel Bay, Arntz and Weber (1970) measured a depth of 10-15 cm penetration in muddy/fine sand. Deeper tracks of c. 20 cm were recorded by Khandriche *et al*., (1986). These may have been caused by "jumping" otter boards, resulting from a course change by the fishing vessel or by the particular bottom topography.

Krost *et al*., (1990) mapped otter trawl tracks in Kiel Bay using side-scan sonar, where otter boards of several hundred kg. are the standard gear in use. They found that single otter board tracks range in width from c. 0.2-2 m and their depths reach 0.3 m. In general, however, the width of the tracks is generally less than 1 m although the tracks of boards that have "jumped" or "skipped" are sometimes wider, usually between 1 and 2 m. Tracks themselves may be at least 5-10 cm deep and probably reach about 20 cm in certain parts. Depressions, probably resulting from bobbins attached to the foot rope of the net, were directly measured by divers and found to penetrate to a depth of 2-5 cm.

Sediment Profile Images (SPI) of the trawl doors of the Irish *Nephrops* trawl indicate that they may penetrate about 14 cm into the sediment surface. This was seen in the well oxygenated muddy sediment in the North Western Irish Sea, Ireland, when investigating the direct impact of this trawl (Fonteyne *et al.*, 1998). Unfortunately, this could not be confirmed by ROV video footage as sediment resuspension obscured the video images.

Margetts and Bridger (1971) concluded that on sand or muddy sand the trawl did not appear to penetrate deeply into the seabed, but that on muddy grounds the trawl mark lasted for several hours. In general, the effect was not noticeably different than found with the otter trawl experiments of Bridger (1970) but it was felt that the results were dependant on environmental conditions and that more study was required.

The duration of otter trawl tracks is dependant on the substratum type and the degree of fishing intensity. In coarse sandy areas, the track will be of short duration due to low penetration by the otter boards and the restoring action of waves and currents (Krost *et al.*, 1990). However, in more sheltered areas such as a Gareloch, a Scottish Sea loch subject to extremely low fishing pressure, very faint marks could be discerned 18 months following experimental trawling (Tuck *et al.*, 1998).

1.2.1.2 Beam trawl studies

Due to the pressure of the beam trawl on the sea bed, parts of the gear penetrate to some extent into the sea bottom. The pressure exerted by a beam trawl on the seabed is relatively low, on average about 2 N/cm^{-2}, and does not increase considerably with the size of the gear (Fonteyne *et al.*, 1998). The penetration depth largely depends on the nature of the bottom (Margetts and Bridger, 1971; Bridger, 1972; de Groot, 1972; Anon., 1973).

Depending on the sediment type, weight of the beam and shoes, weight per unit length, number and spacing of tickler chains, towing speed and tidal conditions, a beam trawl will cause a more or less distinct track, estimated to persist for up to 52 hours (Margetts and Bridger, 1971; de Groot, 1972; Bergman *et al.*, 1990; Fonteyne *et al.*, 1998). The disturbance is most distinct on muddy or soft sandy grounds. On hard sandy ground, the tracks are difficult to detect, being a more smoothed path. On very soft grounds the tracks are ill-defined and are soon erased. The most visible tracks are made by the sole plates. Margetts and Bridger (1971) observed sole plate marks 80-100 mm deep on muddy sand but only 15 mm deep on sandy ridged ground. The tickler chains seem not to be in firm contact with the bottom and will only exert a limited pressure on the seabed. Successive layers of sediment will be brought into suspension but will settle again after the gear has passed. This is not likely to cause a problem in areas where natural sediment movement due to the effect of tidal action and gales is high (Anon., 1973; de Groot, 1984; Anon, 1988). Based on measurements made with implanted markers in the sea bed, Bridger (1972) concluded that only the surface of the soil will be disturbed by a tickler chain (c. top 10 mm). Even with an array of 15 tickler chains (1478 kg) operating on mud at a low speed of 2.2 knots, the penetration depth did not exceed 30 mm.

A later study by Blom (1990) using a light 12 m beam trawl, with a fishing speed of 6 knots, indicated that the tickler chains were nearly stiff under tension and again were not in continuous contact with the bottom. The trawl shoes however, made a visible track on the sea bed. This bottom contact results in gradual chafing of the ground rope chain, but only the lower part of the vertical shackle is affected, which indicates that bottom penetration of a single chain is of an order of magnitude of a few centimetres. This estimate is in line with that observed by Bridger (1972).

Laban and Lindeboom (1991) reported on the penetration studies of the 1990 BEON programme. If fishing gear disturbs the sediment and the sediment re-settles after passage of the gear, it may be expected that sediment characteristics will be changed as deep as the penetration depth of the beam trawl. A method to determine the penetration depth is to use the measurement of sediment characteristics which show a distinctive depth profile. Such a profile must be measured before and after fishing whereby changes in the profiles may indicate the depth at which the gear has influenced the sediments. Based on the absence of parallel lamination in the top few centimetres of cores taken in the track of the trawl compared with cores taken outside the beam trawl, the disturbance is 7 cm minimum.

Based on the presence (and absence) of foraminifera assemblages in bottom cores taken inside and outside the beam trawl track, Laban and Lindeboom (1991) concluded that the penetration of the beam trawl was about 6.5 cm. Profiles of reciprocal formation factors were also measured by means of a resistivity probe. This probe measures the electrical resistance inside the sediment. Box core samples were sub sampled (cores taken in- and outside of the trawl track), and from the measurements it could be concluded that the trawl penetrated 4-5 cm into the sea bed during fishing. Summarising all results obtained with geological and sedimentological methods the average penetration depth of a beam trawl was deemed to be between 4 and 7 cm.

Penetration depth was again studied in the 1991 BEON programme. Laban (1992) tried to establish the penetration depth of a beam trawl in cores taken in-and outside of the trawl track. The results were not optimal due to various circumstances but indicate, via a sedimentological description of the cores (lackerpeel method), a penetration depth of 5-6 cm. How deep a trawl penetrates into the bottom will also depend on the substratum hence the spread of 1.5 cm for sole plates on light beam trawls and up to 7 cm for tickler chains on heavy modern beam trawls.

Under the framework of the IMPACT-I programme, the penetration depth of a 12 m beam trawl was estimated by recording changes in the depth-frequency distribution of nematodes in sandy sediment (Santbrink and Bergman, 1994). The presence of infauna species in the trawls, coupled with a decreased density of infauna following trawling, indicated that the penetration depth was approximately 2-4 cm.

From the presence of benthic infauna (*Arctica islandica* and *Echinocardium cordatum*) in the catches of a 12 m/7000 kg beam trawl operating on a hard sandy bottom, Bergman *et al*..(1990) concluded that the tickler chains, possibly only in part of the trawled area, penetrated to a depth of at least 6 cm. The IMPACT-II project (Lindeboom and de Groot, 1998) estimates the penetration depth of a beam trawl as 1 to 8 cm, depending on sediment characteristics and rigging of the gear.

However, there are unsubstantiated statements as e.g. by Laane *et al.*, (1990) in a report to the Ministry of Transport and Public Works, Tidal Water Division, stating that beam trawls penetrate 20 cm deep into the sea bed.

Rauck (1988) noted that the penetration depth of beam trawls is estimated to range from 2-6 cm in hard and sandy bottom up to 10-30 cm in soft and muddy ground.

1.2.1.3 Otter and beam trawl comparisons

A comparison was made by Houghton *et al*., (1971) between the catch from a 700 hp beam trawler and two otter trawlers (175 and 1060 hp) in the Irish Sea. It was clear that the beam trawler was more efficient in catching flatfish, particularly sole, than the two otter trawlers. The beam trawl also caught more buried or partially buried invertebrates. From catches of *Acanthocardia* and *Echinocardium* the authors inferred that the beam trawls affected the top layer of the sea bed up to 10 to 20 cm deep. If the presence of these animals is indicative of deeper penetration by beam trawls, the significantly lower number of these species in otter trawl returns can therefore lead to the assumption that otter trawls penetrate less deeply into the sediment.

More recent research in the North Sea by Craeymeersch *et al*., (1998) indicated that the lower catch efficiency of the otter trawl for many invertebrate species compared to a beam trawl was in part a result of the shallow penetration of this gear due to the absence of ticklers in front of the groundrope.

From Table 1 it can be concluded that the penetration depth of beam trawls on sandy sediment is up to 7 cm but occasionally depths of 10-20 cm are recorded. In muddy seabeds the penetration depth is approximately 1.5-7 cm. For ottertrawls on sandy sediment the penetration depth is up to 5 cm but on softer sediments such as mud the otter doors can penetrate depths of 15-30 cm.

Penetration Depth	**Reference**	**Gear type**	**Substratum**
100-150 mm	Arntz and Weber, 1970	Otter boards	muddy fine sand
a thin layer of top substrate	Bridger, 1970	Otter trawl ticklers	sand
80-100 mm	Margetts and Bridger, 1971	Beam trawls	muddy sand
100-200 mm	Houghton *et al.*, 1971	Beam trawls	sand
0-27 mm	Bridger, 1972	Beam trawls	mud
rather limited	de Clerck and Hovart, 1972	Beam trawls	rough ground
few centimetres	Caddy, 1973	Otter boards	sandy sediment
10-30 mm	de Groot, 1984	Beam trawls	mud, sand
200 mm	Khandriche, *et al.*, 1986	Otter board	mud
a few centimetres.	Blom, 1990	Beam trawls	sand
= 60 mm	Bergman *et al.*, 1990	Beam trawls	fine to medium hard sand
5-200 mm 20-50 mm	Krost *et al*, 1990	Otter board rollers on foot rope	mud, sand
200 mm	Laane *et al.*, 1990	Beam trawls	mud, sand
20-300 mm	Rauck, 1988	Beam trawls	mud, sand
5-170 mm	Rumohr (in Krost *et al*, 1990)	Otter board	mud, sand
40-70 mm	Laban and Lindeboom, 1991	Beam trawls	fine sand
50-60 mm	BEON, 1991	Beam trawls	fine sand
few cm. - 300 mm	Jones, 1992	Otterboards	deepest in soft mud
20-40 mm	Santbrink and Bergman, 1994	Beam trawls	fine to medium sand sediment
15-70 mm	de Groot, 1995	Beam trawls	substratum dependant
~ 140 mm	Lindeboom and de Groot (edit.), 1998	Otterboards in the Irish Sea	mud

Table 1. Summary of bottom trawling gear penetration estimates

1.2.2. Sediment re-suspension

Krost (1990) investigated the effects of otter trawling, particularly the otter doors, in Kieler Bucht (Kiel Bay) in the Western Baltic. While he concentrated on the release of nutrients due to trawling activities, the dislocation effect on benthic macro-fauna was also studied. Samples were taken from otterboard tracks and control areas. Densities of infauna tended to be more strongly affected than those of epifauna. Abundance tended to be more affected than biomass. Most of the effect was caused by the turbulence induced by the boards, rather than by direct contact. Trawl boards caused a pressure wave in front of the door as they ploughed through the sediment leading to the generation of sand clouds from suspended sediment on the suction (low pressure) side. Suspended sediment plumes have also been recorded as a result of bottom contact from other parts of otter trawls such as the bobbins (Main and Sangster, 1978, 1981), although these tend to be smaller than those produced by the otter boards.

The sediment cloud generated by trawl doors and by tickler chains contributes to fish capture (Main and Sangster, 1978, 1981; de Groot, 1984). Margetts and Bridger (1971) also noted that the effect of an array of chains on the sediment cloud is dependant on the distance between the chains, the towing speed and sediment particle size. At any one speed, a number of tickler chains spread far apart would not be expected to scour as deeply as the same number of chains positioned close together. A greater distance between chains allows more time for the sediment to resettle however, presumably reducing the size of the sediment cloud.

1.2.3 Habitat disturbance

It is clear that mobile bottom fishing gears scrape and plough up the substratum, generating sediment resuspension as well as direct faunal mortalities. Such direct effects will result in post-trawling stress, such as habitat modification, which in the short term may reduce habitat complexity resulting in fluctuations within benthic communities. Apart from physical disruption, the bottom disturbance renders disturbed and damaged invertebrates susceptible to predation while colonies rooted in the sand are dislodged. The magnitude of these effects is dependent on the force induced by the gear on the sea-bed, towing speed, nature of the bottom sediments, strength of tides and currents, and the frequency of impact. The duration of the effect depends on hydrographical circumstances, i.e. surface disturbances caused by storms as well as the ability of invertebrates to resettle and recolonise disturbed areas. The more stable the environment and the greater the water depths, the longer it takes for the ecosystem to recover.

Benthic infaunal communities are by no means constant over time, being a mosaic of patches in various states of climax or recolonisation (Connell, 1978; Grassel and Saunders, 1973). This is especially true in shallow seas on the continental shelf at depths of <100m where the majority of demersal fishing occurs. Here, benthic communities tend to experience continual disturbance at various scales (Hall, 1994). Holme (1983) reported on natural fluctuations in the benthic communities in the western British Channel. Temperature, the strength of tidal streams and weather conditions all have an effect on the presence of certain species. Such large scale natural disturbances form a background against which other small scale disturbance events, even when frequent, may be masked. Communities in these less than uniform environments tend to be quite resistant to disturbance, as animals that may recolonise a disturbed area are usually species already dominant in the community (Boesch and Rosenberg, 1981). However, a threshold scale must exist for the frequency and spatial scale of disturbance effects at which lasting ecological effects may occur, even against a background of natural disturbance. Indeed, in intensively fished areas such as the southern North Sea background levels may have been exceeded resulting in long term changes in the local benthic community to such an extent that it becomes adapted to regular fishing disturbance.

Detecting long term changes in benthic fauna attributable to fishing activities is problematic due to the absence of long term data sets as well as the paucity of comparable undisturbed areas. Rauck (1985) calculated, based on effort data of 1975, that in some areas of the North Sea every m^2 is fished three to five times per year with "certain areas being trawled even more than 10 times per year resulting in complete benthos depletion". He advocated more elaborate investigations. In addition, the ICES Study Group on The Effects of Bottom Trawling reporting in 1998 on the state of the art (Anon., 1988) concluded that the considerable increase in vessel numbers and gear sizes since 1972 called for further research and advocated a pilot study to investigate the practicality of measuring the effects of bottom trawling on benthic communities in a fished and unfished area.

Schwinghamer *et al*., (1996) described an in situ experiment to quantify the immediate impacts of trawling and the recovery of the affected sediments over time. The authors used fractal geometry to describe sediment structures. Acoustic signals were processed by Hilbert-transformation to the fractal form. Trawled tracks were sampled with a remotely operated grab featuring an acoustic array of 40 elements to record a digital bottom image. The upper 4.5 cm layer of the sediment was analysed in five depth strata. The acoustic data showed that the structure of the upper layer of the sea bed was significantly altered by trawling. The study also indicated that megafauna were reduced in numbers, although at the time of publication not all the samples were fully analysed in terms of species composition. The authors concluded that the disturbance by trawling consisted of a reduction in the fine-scale complexity of the substratum.

Video footage following passage of an otter trawl in the well oxygenated muddy *Nephrops* grounds in the North Western Irish Sea, Ireland, showed fewer openings of *Nephrops* burrows in the areas swept by the net (Tuck *et al*., 1998). This may indicate that the delicate and complex structure of the burrow systems collapsed and were filled in by the passage of the gear. The long term energetic costs of repeated burrow reconstruction may have long term implications on the growth or fecundity of individuals.

The effects of trawling on the eastern Canadian continental shelf seabed were presented by Messieh *et al*., (1991). Otterboards were observed to scour the sea bed and generate turbulent wakes of sediment (sand clouds) and detritus stirred from the bottom. A list of potential impacts is given, which include: incidental mortality and physical damage of marine organisms by direct contact with gears, increased susceptibility to predation, alteration of the chemistry and texture of the sediments that may render the sea bed habitat less suitable for some species, sediment resuspension affecting filter-feeders and gills of marine organisms as well as eggs and larvae, but also cause the outspread of toxic contaminants, and increased rates of nutrient flux. It was concluded that it is clear that extensive fishing activities can produce long-term changes in sediment characteristics and the benthic community structure.

This is especially true of epifaunal benthic communities. Studies into the effects of mobile gears on such communities were extensively reviewed in the IMPACT-II report (Tuck *et al*., 1998). The two main effects were a modification of the substrata and the removal of biogenic taxa with a subsequent decline in the abundance of species and the communities associated with them. Such biogenic taxa increase the complexity of the epibenthic habitat, creating specialised environmental conditions (*i.e.* by altering local hydrographic conditions) which facilitate the developments of specialised associated communities. Loss of such infrastructures therefore tends to affect the viability of these associated species and prolongs the recolinisation process. Indeed, when subjected to intense fishing pressure, marine communities, which are dominated by long-lived suspension feeders, are most likely replaced by assemblages of opportunistic deposit feeding species and mobile carnivore epifauna.

Auster *et al*., (1996) reviewed the impacts of mobile fishing gear on sea-floor habitats in the Gulf of Maine. They observed and compared three areas in 1987 and 1993, Swans Island, which is a closed area for fishing, Jeffreys Bank, previously inaccessible to mobile fishing gears, but resurveyed after six years of fishing and Stellwagen Bank, fished by mobile gears regularly. They found that the percentage cover by benthic organisms was reduced due to fishing activities. Epi-benthic animals that anchor in the sand were removed by mobile fishing gear. They concluded that mobile fishing gears do alter seafloor habitats and reduce habitat complexity. This may lead to increased predation on juveniles of marine species. In addition to removal of targeted species, fishing also seems to affect ecosystem productivity.

The ICES Benthos Ecology Working Group prepared a report in 1991 in which current research was reviewed. Reports were given for Norway, Sweden, Germany, Netherlands, France, United Kingdom, United States and Canada. The conclusions were that the interest to understand the impacts of physical disturbances on the benthic ecosystem in government agencies, industry and the public had grown. It was stated that anthropogenic disturbance of the seafloor can indeed affect benthic habitat and organisms. Effects are: change in grain size of surface sediments, change in chemical fluxes between sediments and adjacent water, change in erosion potential of sediments, trawlpath benthos mortality, dislocation of animals from their habitat, reduction in species diversity, change in the relative abundance of species, damage to organisms, change in the patchiness of organism distribution, loss of other species that provide food or shelter. The document advocated more research and international co-operation.

1.3 Effects on non target fish and benthic invertebrates

Beyond long-term changes in sediment characteristics and the benthic community structure, benthic species are directly affected by demersal fishing gears. In some fisheries, the bycatch of non-target fish and benthic invertebrate species can comprise a large proportion of the catch. Because these species are often of no commercial value they are discarded by fishers, together with undersized target fish. Pauly and Christensen (1995) estimated that c. 27 million tonnes of bycatch are discarded each year world-wide, with 789 000 tonnes being discarded from the North Sea (Camphuysen *et al*., 1993; Garthe *et al*., 1996). Of this, 149 700 tonnes consist of benthic invertebrates. It is estimated that between 20 and 70% of the total discarded material may be consumed by seabirds (Blaber and Wassenberg, 1989; Camphuysen *et al*., 1993; Evans *et al*., 1994; IMPACT-II report (Lindeboom and de Groot, 1998)). The remainder sinks to the seabed whereupon it becomes available to midwater and benthic predators and scavengers (Wassenberg and Hill, 1990; Hill and Wassenberg, 1990). The discard component consumed by midwater fish and marine mammals is not well understood, presumably as a result of sampling difficulties. What does sink to the bottom may be eaten by a variety of crustacean and fish scavengers, providing an addition to the maintenance food requirements.

The IMPACT-I report presented an analysis of the catch composition of 4 m and 12 m beam trawls used for sole fishing in the southern North Sea. Beam trawls catch on average 2 kg of discard fish and 4-5 kg of invertebrates for 1 kg of market fish. The sole fishery alone is estimated to annually discard about 150 000-190 000 tonnes of discard fish and 65 000-85 000 tonnes of dead invertebrates (Fonds and Groenewold, in press).

It is clear, therefore, that demersal trawling removes large quantities of organic matter from the seafloor to the surface where significant quantities are removed for human consumption, or as in the case of most discarded material, as food for surface scavengers. The impact of this efflux of material from the seafloor is not well understood (Evans *et al*., 1994). This is surprising given that benthic animals tend to be the basis for the food chain on which demersal target species depend.

In addition to the above, direct contact of trawling gear via ground rope, chains and bobbins, sweeps, doors, chaffing mats or parts of the net bag etc. results in scraping and ploughing up of the substratum. This can displace, damage or kill a proportion of the epibenthic and infaunal animals in the path of the trawl. Some animals may also escape the cod-end, but subsequently die. This 'non-catch' mortality provides food for scavengers. Fish, more so than other species, are especially able to capitalise on this food source, being able to migrate rapidly into trawled areas. Indeed, the behaviour of scavenging and predatory fish species attracted to such disturbed areas is frequently exploited by trawlers who will fish a recently towed line.

One of the earlier publications of studies into the effects of trawling on seabed organisms is found in Graham (1955). He reports about experiments carried out in

1938 and 1939 in the North Sea near the Dutch coast on plaice grounds. It is interesting to read about the methodology applied, involving the use of unfished control areas and techniques to bring samples onboard by grabbing and dredging. The author concluded, however, that although some animals were proven to get damaged (sea urchins), there was no marked difference between the benthic communities within and outside the trawled areas. The paper gives no information about the trawls but the fact that one tickler chain was used. The validity of the conclusion for present gears is doubtful therefore.

De Groot and Apeldoorn (1971) investigated the impact of beam trawls on fish and benthic organisms caught in the trawl nets. Two trips were undertaken on RV TRIDENS and RV WILLEM BEUKELSZ on grounds in the North Sea near the Dutch coast. The trawls used had beam lengths of 6 m and mesh size of 20 mm and were rigged with 0-5 tickler chains. Tows were made with 15 minute duration. The damage and mortality of both invertebrate and vertebrates species caught in the net were analysed and presented in %-groupings. Apart from direct effects due to the chains, it was also assumed that chafing of the belly along the bottom caused considerable damage to *Tubularia*. It should be noted that many species also suffer from deck exposure even when not affected severely by catching. The development of onboard sorting equipment in the 1980's may have decreased this effect. The work also clearly demonstrated the rise in sole catch with increasing number of tickler chains.

In his review of 1984, de Groot describes effects of trawling on various benthic species caught in the net. For *Coelenterates* he summarised the effects as follows: *Tubelaria*, *Ctenophores* and *Scyphozoans* are mostly damaged by the net in the belly of the trawl, irrespective of tickler chains used. Little damage is done to *Bryozoans*. *Nemertea* (ribbon worms) are damaged to some extent, mainly by the tickler chains, but these worms are only caught in small numbers as they are easily swept through the meshes. *Annelids* (bristle worms) are damaged considerably. Of the crustaceans, *Eupagurus* are caught in large numbers but seem to survive catching and processing. *Portunus* are partly damaged and like *Eupagurus* their numbers increase with the number of tickler chains. *Crangon* catches were only slightly increased with more chains. All *Cephalopods* are killed or badly damaged, but no relation was found with the number of tickler chains applied. Bivalves (*Ensis* and *Solen*) are damaged due to the ploughing effect of the chains, but *Spisula*, *Mactra*, *Venus* and *Cardium* sustain ticklers well. *Echocardium* is heavily damaged by the chains. The number of *Asteroids* caught rise rapidly with the number of chains, but they are not damaged to a great number. *Ophiuroids* (Brittle stars) are mostly damaged but the catch does not rise quickly when more chains are fitted.

Creutzberg *et al*., (1987) investigated the effect of increasing the number of tickler chains on a light 5.5 m beam trawl. The range tried was between 0 and 6 ticklers with a shackle size of 55 x 35 x 12 mm. The codend mesh used was 10 mm. The groundrope was fitted with wooden rollers of 70 mm diameter, and the towing speed was around 4 kn. For each configuration a total of 7 hauls were made. Each tow lasted for 5 minutes and four different locations were visited. The experiments were carried out in January and October of 1977. The effect on the total catch is given for a number of species (i.e. *Solea solea, Limanda limanda, Buglossidium luteum, Pomatoschistus spp., Macropipus holsatus, Crangon allmani, Crangon crangon, Asterias rubens, Ophiura texturata*). In muddy grounds the effect of the number of chains on the catches is non-significant, but on sandy grounds the number of tickler chains show a positive effect on the catches of species that burrow occasionally and species that cling tightly to the bottom. In some species the numbers caught reached an asymptotic level with increasing number of chains (*e.g. Limanda limanda*), whereas in other cases the increase in catches was still significant even when reaching the maximum of 6 chains (*Solea solea*).

Bergman *et al*., (1990) investigated the effects on benthic fauna of fishing with 12 m and 4 m beam trawls for sole. The mortalities varied per species but some overall estimates include: molluscs 0-85%, crustaceans 4-80%, annelid species 0-60%, echinoderm species 0-45%.

From IMPACT-II studies it was concluded that for a number of invertebrate species (gastropods, starfish, crustaceans, annelids) direct mortality rates due to a single trawl (beam and otter) ranged from about 5-40 % of the initial densities in the trawl track. For bivalve species, this ranged from 20-65 %. Direct mortality rates of a 12 m beam trawl were not higher than those of a 4 m beam trawl. For all the species considered, the direct mortality was largely attributed to the mortality of animals that remained in the trawl track, either as a result of physical damage inflicted by the passage of the trawl or indirectly due to disturbance, exposure and subsequent predation. Mortality of animals caught in the net was of minor importance. The annual fishing mortality in megafaunal populations (diameter > 1 cm) in the Dutch sector of the North Sea ranged from 5-40 % with half the number of species showing values of more than 20 % (Bergman and van Santbrink, in press).

In a study of the effects of otter trawling on the *Nephrops* community of the northwest Irish sea detailed in the IMPACT II report (Tuck *et al*., 1998), video footage following the passage of a trawl indicated that sessile epifauna such as seapens (*Vigularia mirabilis*) and fanworms (*Sabella* sp.) remained attached to the substratum. However, injury to the distil portion of seapens was commonly noted presumably as a result of abrasion by portions of the gear. In addition, the tubes of fanworms appeared to protrude further. This may render them more susceptible to predators. While both seapens and *Sabella* sp. were commonly found in the bycatch of the *Nephrops* trawls, it would appear that disturbance *per se* rather than removal of sessile benthic epifauna is the most common result following the passage of a single trawl.

A comparison of total benthic invertebrate mortality following passage of an otter trawl and a beam trawl, indicated that mortality was lower for otter trawling in silty areas (Bergman *et al*., 1998). This is probably indicative of a lower penetration depth by the otter trawls. Such differences were not found in a study in a sandy area in the North Sea. In these studies the total mortality due to the otter trawl doors was not measured as logistically it is impossible to ensure that a single door track is sampled. However, even if mortality due to the doors is higher than in the path of the ground rope plus bridles, this should only cause a slight underestimation of total mortality in the path of the otter trawls. This is because the width of the path travelled by the two doors is less than 10 % of the width of the ground rope path.

Lindeboom and de Groot (1998) concluded from the E.U. research project IMPACT-II, that trawling activities have had a distinct effect on the benthic communities in the North Sea and Irish Sea. In general, opportunistic (small size, fast reproducing) species increased in abundance while sensitive (large size, fragile) species declined in numbers. Other possible causes, such as eutrophication, climatic fluctuations and/or pollution, can not be accounted for to explain the changes in the ecosystem. By investigating the effect of trawling in an unfished area it was found that this produces clear long term effects on both epi- and in-fauna. It was concluded that fishing mortality can only be reduced by a reduction in trawling effort, spatial restrictions and alternative gear designs. The authors advocated more research to develop these alternative techniques.

1.4 Discussion

1.4.1 Physical and biological impact of trawling

From the above it can be seen that the side-effects of trawling on the bottom may be summarised under scraping, penetration and pressure of gear parts on the sediment, sediment suspension/burying and the effect on benthos (i.e. habitat disturbance, direct mortality, exposure to predators and removal of non-target invertebrate benthic species).

De Groot (1984) reviewed research into impacts of bottom trawls on the benthos, in particular the work done under the auspices of ICES in the early 1970's, and some direct observation studies in the early 1980's. He noted that under normal working conditions, bottom trawls influence only the top layer of the sea bed and reported that penetration depths were estimated to be up to 30 mm on muddy grounds, and 10 mm on sandy grounds. He concluded at the time that it is not unthinkable that there is a long term effect and shift in the macro-benthos composition in the North Sea, but this would not cause a shortage in food for the fish stocks nor constitute a major thread to benthic life. As fisheries is accepted to support the food supply in the world, and the damage is relatively small, it may be considered to be acceptable.

IMPACT-II studies did reveal that the long term impact of trawling can be observed in some marine communities where long-lived suspension feeders were seen to be replaced by assemblages dominated by opportunistic short-lived deposit feeders.

However, more recent studies have concluded that the disturbance by trawling consisted of a reduction in the fine-scale complexity of the substratum (Schwinghamer *et al.*, 1996). In addition, Auster *et al.*, (1996) noted that mobile fishing gears do alter seafloor habitats and reduce habitat complexity. This may lead to increased predation on juveniles of marine species, including commercial fish species, as the more complex a habitat the harder it is for predators to find food. This may be of little significance when stocks are high but would be important if stocks were depleted. Therefore, in addition to the removal of targeted species, intensive demersal fishing may also affect ecosystem productivity.

Jones (1992) in his review of the impacts of trawling on the seabed reiterated that otter board leave distinct imprints on the seafloor. He noted that the depth of these tracks depends on the weight of the board (which can weigh up to several tonnes), the angle at which the boards are towed at and the nature of the substratum. The depth of the grooves, therefore, is extremely variable ranging from a few cm's to 30 cm deep. Bobbins and chains also leave recognisable tracks as noted above (Krost *et al*., 1990) and may skim off surface sediment layers.

De Groot (1995) reviewed the ICES studies into the effects of beam trawling and the studies undertaken in The Netherlands. He summarised the work previously undertaken and concluded that the penetration depth of a beam trawl is between 1.5 and 7 cm. The penetration depth depends on the nature of the substratum (silt, mud, sand, hard sand, gravel or rocks), and opposed the view of Laane *et al*., who stated that beam trawls penetrate as much as 20 cm.

A summary penetration depth estimates is shown in Table 1. It is clear that the estimates vary greatly but this is partly due to the differences in methodology used with direct measurements of the penetration depth being rare (e.g. Bridger, 1970; Margetts and Bridger, 1971). In many cases the depth is inferred from other information, e.g. the presence of certain animals in the catch which live at a known depth in the substratum (Houghton *et al*., 1971; Bergman and Hup, 1992).

The meaning of penetration depth in relation to benthos mortality may be dubious. Obviously, when animals are living in deeper layers than gears affect, the chances of damage or capture are reduced. On the other hand, the repetition in passage of many gear components (i.e. an array of beam and net tickler chains) will increase the number of collisions with animals on the sea bed. In addition, successive sediment layers are believed to be scraped off by the tickler chains, but resettlement of suspended sediment while dependant on tidal currents, causes the penetration depth not to increase after successive hauls. The mechanism of catch is rarely observed however. It may be the case that some deeper living animals are torn out of the sediment by the chains getting hold on their siphon.

While the debate is not yet closed, the majority of scientists seem to agree, that for beam trawls, the penetration depth varies between 15 and 70 mm. For otter boards, values up to 300 mm can be reached in soft sediments. Depressions probably resulting from rollers attached to the foot rope of otter trawls may penetrate to a depth of 2-5 cm. Claims for larger values do not seem to be justifiable.

With regard to sediment suspension, Krost (1990) cautions about assuming mortality in cases of low abundance in the trawl track, as animals might have been displaced by turbulence. The sediment cloud generated by trawl doors and by tickler chains also contributes to fish capture and therefore is an important component that must be considered when investigating modifications to fishing gears. However, the effect of an array of chains on this sediment cloud is dependant on the distance between the chains, the towing speed and sediment particle size. At any one speed, a number of tickler chains spread far apart would not be expected to scour as deeply as the same number of chains positioned close together. A greater distance between chains allows more time for the sediment to re-settle, presumably reducing the size of the sediment cloud, but also allowing a contribution to fish capture.

Direct contact with the seabed and resuspension of the sediment by the gears results in habitat disturbance, a reduction of habitat complexity, mortality of invertebrate animals remaining in the trawl track and to a lesser degree of animals caught in the net. The extent of this is dependant on the type of gears being used, the penetration depth and the intensity of fishing activity. It would seem logical therefore that a reduction in the number of gear components in contact with the substratum, a reduction in penetration depth in soft sediment and the use of less rigid trawl types in rocky areas, coupled with a decrease in the intensity of fishing, would reduce the extent of habitat disturbance and direct mortality in bottom fauna. Ground rope and chain configurations designed with this in mind (e.g. roller ball, parallel chains, alternative methods of stimulation) may be beneficial in this respect, although the effect on commercial catches should be a major consideration.

Beyond the displacement, damage and mortality to a proportion of the epibenthic and infaunal animals in the path of the trawl, demersal trawling also removes large quantities of organic matter from the seafloor to the surface As the efflux of material from the seafloor is not well understood, reducing the quantities of benthic material taken in trawls must be an important consideration for future research.

SECTION 2

REVIEW OF POTENTIAL GEAR MODIFICATIONS

2.1 Introduction

As noted in the previous section, beam trawling, where a trawl is opened with a boom or spar, has been around since the 14th century. It became particularly important in the 1960s as a replacement for otter trawls where chains had been added between the two otter boards to improve flatfish catches. The spreading force of the boards limited the number of chains that could be used. In the intervening years, beam trawl efficiency for catching flatfish has been enhanced by increasing trawl size, weight, and the number of incorporated chains. Since 1988, beam width has been limited to 12 m. In addition to the above, various techniques have been investigated that stimulate flatfish, particularly sole, to become more accessible to trawls. A rake trawl was studied in The Netherlands in 1985, but catch rates were lower than with the tickler chain arrangement, and many fish appeared to be damaged by the steel pins. Research into the use of electrical stimulation for fishing started with shrimp trawling following the observed jumping behaviour of the animals on stimulation. It was also later shown to have potential for catching flatfish, especially sole.

A great deal of research effort was subsequently put into this technique in The Netherlands, Germany, the United Kingdom and Belgium and this has been variously reported upon by de Groot and Boonstra (1970) and by Agricola (1985). In the Netherlands, the key objective of these studies was to decrease gear drag by replacing the tickler chains with a system of parallel electrodes. It was felt that this would improve the fuel economy of fishing vessels, a consideration of great importance, especially in the early 1970s. The system as designed involved an onboard pulse generator, connected through a cable to a capacitor discharge unit built inside the beam. An array of electrodes was placed in front of the ground rope. The method, however, was banned in The Netherlands, in 1988 for political reasons, i.e. fear of a further undesirable increase in fishing effort. This led to a cessation of all related research activities in The Netherlands and also to possibilities of fully commercialising the system. While the potential of this method for reducing trawling effects on benthic organisms was signalled, it was insufficient to redress the embargo on further research and development.

Following the Dutch example, similar electric tickler systems were developed in Germany (Horn, 1976), Belgium (Vanden Broucke, 1973), and the United Kingdom (Stewart, 1979; Van Marlen, 1985; Lart and Horton, 1996), although the design rationale differed in the various systems. Recent developments in high-power electronics (i.e. "sparker" technology) indicate ways of creating a much more robust pulser-unit than earlier designs based on capacitor discharge and thyristor technology.

A relatively large number of tickler chains are used in conventional beam trawls, particularly to catch sole. It is conceivable, however, that the scraping effect of these chains can be altered in such a way that while they remain effective in chasing flatfish out of the bottom, they cause less impact on the benthic fauna (by reducing their weight and/or aligning them longitudinally), or indeed, that the stimulus can be provided by other mechanical means, e.g. water jets, with lessened impact. These approaches would contribute towards decreasing the mortality of invertebrates caused by the passage of gear. BFAFi currently has an ongoing contact with a SME that showed interest in developing a stimulation system using water jet injection involving pumps placed on the beam of a beam trawl.

Small scale research has been carried out on other ways of reducing the bycatch of benthic organisms by RIVO-DLO and NIOZ in The Netherlands. Strategies included: (a) increasing mesh size from 10 cm to 12 cm in front of the cod end, (b) the incorporation of release holes in the lower belly of the net, (c) replacing the tickler chains with brushes, and (d) building a release panel into the trawl from the fourth tickler chain to a second cod end with the aim of guiding benthic organisms out of the trawl (Fonds, 1994). Preliminary trials showed some potential for releasing at least some of the bycatch. The mesh size increase caused a drop in sole catches, had no effect on plaice catches but allowed the release of juvenile dab and benthos. Release holes did not seem to affect flatfish catches, but released shellfish to some extent. The release panel did decrease bycatch of undersized fish and benthos without losing sole, at least during the day.

For most invertebrate benthic species, mortality among animals caught in beam trawl nets contributes only a small fraction to the total mortality (E.U.-projects IMPACT-I and II). Mortality of invertebrates mainly occurred in the trawl path, due to passage of the beam trawl and the tickler chains over the sea bed. This damaged the animals or unduly exposed them to predators and scavengers. It is patent that studies aimed at reducing the impact of beam trawls on benthos will have to focus on the mortality in the trawl path.

The other demersal trawling method to be considered is the otter trawl. To support the current E.U. policy of ‘sustainable development’ for both fisheries and the natural marine ecosystem, a study into the effects of otter trawling for *Nephrops norvegicus* on the benthic ecosystem was conducted by personnel from the Martin Ryan Marine Science Institute, National University of Ireland under the IMPACT II - AIR2-CT92-1664 programme. It contributed general background data that will be essential for the future management of the *Nephrops* fishery in the Irish Sea (Fox *et al*., 1996). Findings to date make a clear case for similar studies on other directed fisheries. Recent studies into gear selectivity in Irish waters have tended to concentrate on reducing non-target and juvenile fish bycatch (*e.g*. E.U. Study Contract BIO/ECO 1993/11, E.U. Study Contract 1994/084), but no attempts have been made to reduce the benthic bycatch or the potential damage of demersal fishing gears to invertebrate benthic species. This is an important omission given that benthic animals tend to be the basis for the food chain on which demersal target species depend. Therefore, if there is a reduction in the disturbance to bottom living animals, there may be a subsequent increased food availability for target species.

The provision of an upper square mesh (at least 75 mm) panel which can be inserted into diamond mesh (of at least 70-80 mm) increases the level of juvenile fish escaping from the net and thus reduces fish discard levels. While no similar provision is made for benthic invertebrates, investigations into the use of drop out panels is well worth investigating. Mortalities among the invertebrates that form the bycatch of otter trawls tend to occur as a result of physical contact during trawling and hauling. Such mortalities may be decreased if the degree of contact with the sea bed is reduced. This may also diminish the mortality rate of animals that remain in the trawl track. Such a scenario could be achieved by the provision of a swivelled rollerball system running along the wings of the trawl which will allow the trawl to move over, rather than through, the sediment. In addition, any such modification may have the added bonus of reducing the hauling force, thereby decreasing the energy required to haul the net across the bottom, reducing catch sorting time, as well as possibly allowing a reduction of damage from debris to nets and to fish within the net.

Further, animals that pass through the trawl mesh can be injured, with possible subsequent mortality. Processing and sorting the catch also results in mortalities. Consequently, studies will have to focus on reducing the benthic bycatch, as well as reducing the possibility of animals passing through the net and receiving potentially fatal injuries. Modifications to the drop-out panels mentioned above, together with additional adaptations to gear that will reduce bottom contact, could lead to a significant level of discard separation in otter trawls.

Despite the fact that otter trawl doors may penetrate soft sediment quite deeply, modifications will not be considered at this time. This is because the width of the path travelled by the two doors is less than 10 % of the width of the ground rope path. This results in significant sampling difficulties make the practical investigation of any modified design unfeasible, and therefore beyond the limit of the current review. However, further studies would well benefit from a consideration of this aspect.

Whereas nets have been refined to reduce the bycatch of non-target and undersized commercial species, few attempts have been made to reduce the bycatch or the potential damage of demersal fishing gears on invertebrate benthic species. What follows is a review of the level of existing techniques that have already been tested together with newly emergent suggestions on reducing benthos mortality. These are assessed in light of any existing information on the consequences for commercial catch, consequences for the seabed, consequences for non-target fish mortality and the consequences for invertebrate mortality.

2.2 Beam trawls

2.2.1 Electrical stimulation

The earliest experiments in this field began in the early 1970's in The Netherlands, Belgium, the U.K., Germany and France. Initially, electrical stimulation was tested on beam trawls that targeted shrimp species. The main objectives of the research were to reduce fuel costs by reducing the towing resistance. This was to be achieved by replacing the tickler chains with an array of parallel electrodes. It was also hoped that the length selectivity of fish would be improved thereby increasing the marketable catch.

2.2.1.1 Consequences for commercial catch

In 1972 the first trials in Belgium began with a shrimp beam trawl fitted with electrodes. The concept was that shrimp and flatfish, conventionally disturbed from the bottom by mechanical stimulation could now be disturbed with a higher efficiency using lighter equipment. The main aim of these initial trials was to evaluate the rigging of the electrodes and the catch composition. Since the electricity produced by the dynamo on board the vessels at that time was 24 V, a transformer was necessary. The use of 220 V was one of the weak points of the system due to crew safety. A pulse generator produced an electric pulse to stimulate the fish with the frequency and amplitude altered by a control unit. On board, a cable connected the pulse-generator to the electrodes. This cable was a second serious drawback to the system however. It caused problems with safety on board and resulted in extra labour. Despite these problems, higher catches of shrimp and sole were achieved using the electrified system.

The second series of experiments were conducted in 1973. Although the distance between the electrodes and the pulse frequency was different, the results were comparable to those experienced in 1972.

In 1976, experiments were carried out on a beam trawl fitted with electrodes for sole fishing. A refined pulse system was introduced with a frequency of between 5 and 10 pulses per second and a tension between 60 and 100 volts chosen. In order to reduce damage to the fish, a short pulse length of 1 ms was applied. The results indicated that the heavy tickler chains rigged in traditional beam trawls could be replaced by lighter ones if electricity was used, without significant loss of catch. Actual pulse length seemed to play an important role in sole stimulation.

In 1977, further electro beam trawl trials were undertaken with cod, whiting and shrimp being the target species. The system showed higher catches for shrimp, but reduced catches for cod and whiting. Contrary to the traditional shrimp fishery, the difference between day and night catches was very low with the electric trawl. For sole, the results were less promising. However, due to reduced weight, the electric beam trawl could be towed at higher speeds and with larger beam lengths.

During the experiments, different numbers of electrodes were tested. The main conclusion was that a distance between the electrodes of 0.75 m was most suitable. If closer, the electrodes often collided causing a short circuit. A larger spacing resulted in a weak electric field. Sole catches were higher with the electrified gear especially during night hauls.

Stewart (1972) describes a number of laboratory experiments where *Nephrops norvegicus* were induced to emerge from their burrows under laboratory conditions as a result of pulsed DC application. He considers that the field strength used in the experiment could be realistically induced in the mouth of the trawl. However, field observations did not elicit the same response (Baker, 1973).

In the early eighties trials were continued both in the lab and in commercial conditions on the study of the electric field between the electrodes of an electric beam trawl. The study looked at electrode configurations that would retain the electric field within the trawl mouth. This insured that the efficiency of the trawl was maintained and prevented damage to animals outside the trawl path.

In the following years continuous effort was put into improving the system. Tests were conducted on both otter and beam trawls where both the cutting rate and the groundrope were altered. While international co-operation between the North Sea states lead to promising results, the development of a pulse-generator which could be fixed onto the gear, was never completed in Belgium.

Therefore, although promising, the use of electric stimulation in trawl fisheries met with a range of practical problems, which in Belgium, during a 15 year period of research were never completely overcome. Consequently, when electric fishing stopped in the Netherlands, the experiments in Belgium also ceased.

The Institut für Fangtechnik, Hamburg, first started research in the field of electrical fishing in 1965 when an electrified bottom trawl was tested on FRV "Walther Herwig". The results of these investigations were not sufficient to justify further development in the application of electrical fishing offshore and in subsequent years the institute concentrated on electrified bottom trawls in the German freshwater lake eel fishery.

Based on the knowledge obtained in the lake fishery, the institute initiated the development of an electrified beam trawl for the German inshore sole fishery in 1975. The aim was to replace the heavy tickler chains with electrodes in the hope of reducing the fuel consumption of the fishing vessels and decreasing the destructive impact of the gear on the sea bed. The pulse generator designed for this purpose delivered pulses of a peak voltage of 82 V and a peak current of 1.95 A at a frequency of 25 Hz.

Comparative fishing trials with electrified and traditional beam trawls resulted in higher catches and improved selectivity in the electrified gear not just with sole but with plaice and cod also.

During the following tests, the electric characteristics of the pulse generator were varied in order to find the optimum configuration. A voltage of 110 V and a current of 1.31 A at every pair of electrodes with a pulse length of 0.51 ms at a frequency of 25 Hz proved to be most effective. A 144 % increase in sole catch weight was obtained. At the same time, the by-catch of benthic organisms and sand was reduced by almost 50 %. In 1985, a modified arrangement of electrodes and lower panel was investigated in order to get a uniform electrical field in front of the groundrope.

Research and development in the field of electrified beam trawls was terminated in 1987 when the German authorities were not prepared to allow electrical fishing on a commercial basis. Since then environmental aspects have become more important in the sea fishery. The destruction of the benthos by heavy beam trawl tickler chains is now considered to be a major disadvantage of this type of gear. Given this point of view, a revival of electrified beam trawls seems possible.

In France, as early as the 1960's, studies were carried out to try and find alternative means of stimulation to catch fish. Most of the effort was put into a system where fish were attracted by light and forced to move towards a pump by means of an electric field. At some stage in the development, a co-operation project was established with Poland. Most of the studies consisted of basic research into the behaviour of fish in electric fields. Based on this knowledge, the specifications of a system which could be commercially used for pelagic fish were defined. Claimed advantages of this method were higher catch ability and a better length selectivity.

2.2.1.2 Consequences for seabed

Although targeted at different objectives (*e.g.* reduction of fuel costs) all experimental electrified beam trawls were designed with electrodes that replaced the array of tickler chains. As a result, the environmental effects on habitat and the benthos may be reduced due to the removal of these chains. This was not monitored during the experiments however and therefore the literature did not reveal any information other than anecdotal statements.

2.2.1.3 Consequences for non-target fish mortality

The effect of electricity on other demersal fish species was also extensively studied in Klaipeda and was reported as being negligible. It was also found that electric currents do not affect reproductive qualities. Plaice were observed to jump off the seabed and rise 1.5-2.0 m from the bottom under the influence of the electric field. The critical frequency for electro-narcosis was found to be around 80-100 Hz with the reaction usually occurring 3-4 sec after exposure. Other frequencies lead to slower responses. Sinusoidal pulse shapes were found to be most effective with certain methods capable of optimising the energy efficiency of the pulsar unit (Malkevicius, 1977).

2.2.1.4 Consequences for invertebrate mortality

No information in literature

2.2.1.5 Other effects

In electric fishing there may also be the release of free ions from toxic metals in the electrodes. Electrode materials are discussed by Stewart (1972). The problem of copper electrode corrosion was circumvented in the Netherlands by using stainless steel electrodes, whereas in the German experiments the electrodes were made of steel chains.

2.2.1.6 Discussion

In the countries involved, system prototypes were developed and tested and in some countries attempts were undertaken to commercialise electric fishing. The developments in the Netherlands almost met this objective when in 1986 a private company built a system for commercial production.

In all the research programmes however, electrical stimulation showed serious drawbacks:

-The need for an extra cable between the vessel and the fishing gear.
-Problems with crew safety when in contact with electrified parts of the system.
-Losses in fishing time in cases of a system breakdown.
-Rather high investment and maintenance costs.

The introduction of electric fishing into commercial fisheries did not take place in Lithuania, as in other countries, because of the following reasons:

-Fishermen showed lack of interest.
-The system was not robust, leading to loss of fishing time.

With the strong current interest in reducing any adverse environmental impact of fishing gears, the concept of electric fishing has new potential, if problems concerning robustness and safety can be solved. New research activities focus on reducing the physical impact of trawled fishing gear on the sea bed. This could be achieved in beam trawls, particularly when the heavy tickler chains or chain mats can be replaced with electrodes, which are lighter in construction. The design of the entire trawl could also be reconsidered. Greater length and species selectivity may be obtained for the target species resulting in considerable bycatch reduction in fish. Clearly, such a design should involve consultation with the fishing industry in order to avail of the practical knowledge and experience on offer. One should realise, however, that proper economic incentives should be given to allow fishermen to remain profitable given the high investment costs involved.

2.2.2 Chain configuration and net modification

2.2.2.1 Alternative Techniques Tested

The Netherlands policy related research on alternative trawl design for the reduction of discard catch was grouped in the BEON (Beleidsgericht Ecologisch Onderzoek Noordzee/Waddenzee) report (Fonds and Blom, 1996). A number of technical studies were done for beam trawls and a number of designs were investigated in 1995. These are listed as follows:

a) *Net with brushes as a replacement for tickler chains*

A number of chains were replaced by polypropylene brushes that rolled over the sea bed, but a total of 6-7 chains was kept.

b) *Net with a separating panel*

This net consists of a normal trawl with a sieve net inside to guide smaller fish and other organisms out of the trawl, while sole are caught by the outer net. The sieve is attached to the fourth tickler from the front and runs up the top panel aft with a separate bag to collect the bycatch.

c) *Bigger meshes in the codend*

The codend meshes were enlarged from 80 mm to 90 mm to release benthos.

d) *Net with large mesh top panel*

This concept was developed in the E.U.-projects FAR-TE-2.554 and AIR2-CT93-1015 to decrease the bycatch of roundfish in beam trawls. The report stated that most of the damaging effect of beam trawls on benthos is due to the tickler chains, and most of the damaged animals are not caught in the net. Net improvements which involve releasing already damaged animals are therefore not very effective. Better alternatives involve changing the mesh sizes, protected areas and methods which involve a substitution for tickler chains such as electrical stimulation.

e) Net with large mesh bottom panel

This technique was also tested by the Dutch on a RV TRIDENS cruise in October 1997. Large meshes with a bar length of 300 mm were cut from the centre of the lower panel right behind the footrope in order to release debris and benthos. The investigators began by cutting out one mesh and gradually increasing the number of holes. They were reinforced with 8 mm chain in the first series of hauls and later with 8 mm SK-60 high tensile rope. A total of 67 hauls were conducted in four weeks with catches from the conventional and the modified trawl simultaneously compared. It is suggested that the depth of the large mesh section might not have been sufficient for the release of benthos. Further research will investigate moving the new section further aft in order to improve results.

2.2.2.2 Consequences for commercial catch

Flatfish beam trawls are rigged with tickler chains or chain matrices and these are a determining factor for the efficiency of the gear. The effect on the catch rate, however, is dependent on the species and the type of bottom (de Clerck and Hovart, 1972; Creutzberg *et al*., 1987; Fonds and Blom, 1996). For burrowing species or species that cling strongly to the bottom like *Solea solea* and *Buglossidium luteum* there is a strong correlation between catch rate and the number of tickler chains, even when that number is very high. In these cases, the curves showing the relation between number of chains and gear efficiency will not show an asymptotic course. A 100 % catch efficiency is not reached. Therefore, in the beam trawl fishery where sole is targeted a maximum number of ticklers will be used. An obvious asymptotic course, on the other hand, was found in the curves for dab and starfish. This was also observed for other species like the dragonet, whiting, gobies etc. where further increase in catches do not take place after X number of chains are used.

These effects are very clear on sandy bottom (Creutzberg *et al*., 1987) but on a muddy bottom the chains seemed to have a limited effect. For some species, especially fish, the chains even seemed to have an adverse effect on the catch rate.

Where brushes were used as a replacement for tickler chains less target fish species were caught, some 70-80 % of the standard net catches. When a separating panel was incorporated into the net the concept appeared to work to some extent, particularly during daytime fishing. Night fishing also resulted in sole catches within the inner section of the net which meant that fewer tickler chains were required. When bigger meshes were placed in the codend there was a reduction in the number of both undersized and marketable flatfish caught whereas a large mesh top panel proved to be effective in releasing whiting and cod. Nets with a large mesh bottom panel showed negligible differences in catches for flatfish compared to standard trawls (Fonds and Blom, 1996).

2.2.2.3 Consequences for Seabed

As yet unknown but preliminary results indicated that where large mesh top panels were used the penetration depth may be increased presumably due to a decrease in the lifting power of the gear.

2.2.2.4 Consequences for non-target fish mortality

As yet unknown

2.2.2.5 Consequences for invertebrate mortality

Where brushes were used as a replacement for tickler chains differences in benthos catches of the modified gear were small and statistically non-significant compared to a standard trawl. It is unknown whether the brushes caused less damage to those animals remaining in the track of the trawl, but not caught.

Bigger meshes in the codend or large mesh top panels did not significantly reduce the catch of benthos (Fonds and Blom, 1996). Nets with a large mesh bottom panel showed negligible differences in catches for benthos and debris compared to standard gears.

2.2.3 Water jet stimulation

The Bundesforschungsanstalt für Fischerei (BFAFi) in Hamburg, Germany began experiments with water jet stimulation in 1996. Given the impact of tickler chains on the seabed, the aim was to replace this gear with a system of water jets. The project was in co-operation with the private company Meyer & van der Kamp GmbH & Co. KG Jadesand, Varel. A first prototype was tested on cruise No. 387 of RV SOLEA in April, 1996 during which cruise video recorded the mechanical effects of the jets on a sandy bottom.

The conventional beam is replaced by two beams connected to enlarged vertical trawlhead plates and trawl shoes. Water pressure is delivered by two electrically driven motors of 55 kW. Initially, these were attached to the top beam, but later they were incorporated into the design beam and powered by an electric cable. A total of 16 nozzles were attached to a lower beam, to which rubber hoses were connected to allow flexibility when hitting obstacles on the sea bed. In a later version, the nozzles were made of separate units connected with rubber hosing and brought back closer to the groundrope in order to shorten the time between stimulation and footrope passage. This system is still under investigation.

Catch comparisons were made on RV SOLEA in and on RV TRIDENS in October 1997 and March 1998. During these experiments it was felt that the distance between the stimulus and the groundrope had to be reduced and the groundrope shape was amended.

2.2.3.1 Consequences for commercial catch

The analysis of twenty hauls on RV TRIDENS in the third week of March 1998 revealed that catches of sole, plaice and dab fell considerably short for the 4.5 m water jet beam trawl compared to a 4.5 m standard net. The length-frequency distributions did not show any significant change in selectivity.

2.2.3.2 Consequences for Seabed

As yet unknown

2.2.3.3 Consequences for non-target fish mortality

As yet unknown

2.2.3.4 Consequences for invertebrate mortality

On the TRIDENS experiments of March 1998 a number of benthic species were also analysed. Nets fitted with water jets revealed lower catches of swimming crab *(Liocarcinus)* and masked crab *(Corystes cassivelaunus),* common starfish *(Asterias rubens)*, hermit crab *(Pagarus bernhardus),* but higher catches of edible crab *(Cancer pagarus)*, shore crab *(Carcinus maenas)*, and no difference in whelks *(Buccinum undatum)*. Conflicting results were found for: starfish species *(Astropecten irregularis)* and sea mouse *(Aphrodyta aculeata)*. Catches of these species were very low however. Changes in mortality rates of invertebrate species in the trawl track were not studied. Further research under the current project will provide more definitive results.

2.3 Otter trawls

2.3.1 Electrical stimulation

Electro otter trawls

Research in Belgium also involved a basic study on the reaction of Norway lobster towards electric pulses. Variations in pulses, pulse lengths, frequencies and tensions were tested. The trials were undertaken in an aquarium where the environmental conditions of Norway lobster were simulated. It became clear that larger prawns reacted sooner to the pulses than smaller ones. The most efficient stimulation pattern was determined with the aim of applying it to a commercial otter trawl. The system, consisting of electrified ticklers that were already tested on beam trawls, was now tested on a commercial otter trawl.

Electrical stimulation was also investigated in the Institute of Klaipeda, Lithuania (Masimov and Toliusis, personal communication, 1996). The species under investigation were: Baltic cod, herring, flounder, rainbow trout, shrimp and Japanese scallop. Anode electrotaxis was studied intensively in pulsed electric fields and under direct current (Daniulyte *et al.*, 1987; Simonaviciene, 1987; Daniulyte and Petrauskiene, 1987). The effect of electric current was also tested on physiological parameters (Vosyline, 1987), electrocardiograms and the heart rhythm of fish (Kazlauskiene and Daniulyte, 1987; Kazlauskiene, 1987).

2.3.1.1.Consequences for commercial catch

The electrified otter trawl had a higher catch ability for sole. It also improved selectivity, catching less undersized and more market sized individuals. An alternating pulse also appeared to reduce the electrolysis effect. The results indicate that in this case catches are higher compared to the pulses from a direct current. As previous studies indicated, the system has a serious drawback i.e. the extra cable needed to connect the electrodes with the energy source. Extra manpower is necessary for hauling the cable and damage to the cable also causes loss of fishing time.

Electrical stimulation trials have also been undertaken in three small fresh water lakes in northern Germany i.e. Witten See, Ratzeburger See and Steinhuder Meer. Here it was shown that catches of eel could be increased by a factor of 10-20 using the electrified system. Despite this, commercial application of the system failed due to the fact that there were no boats available with sufficient engine power to tow the gear.

2.3.1.2 Consequences for seabed

Otter trawls equipped with an electric stimulation system were also tested in Belgium. Initially targeted at the *Nephrops* fishery, it later proved to also increase the sole catch. Other advantages included improved selection characteristics, with an obvious reduction in catches of undersized fish and an increase in the landing of fish above the minimum size. The research on electrified otter trawls in the U.K. proved more difficult because of the difficulty in maintaining the gear in a consistent geometry. The fuel savings were less and a number of handling problems were encountered. As a result, the otter trawl investigations were not considered to be as promising as beam trawl studies. Despite much research, by the late 1980's commercial application of electrified gears was not forthcoming and effort in this area of fishing ceased.

2.3.2. Square mesh selector panels

Conventionally, most otter trawl netting is constructed from diamond shaped meshes. Drag from the codend causes this mesh to elongate considerably with the result that the netting takes on a tunnel-like appearance. The escape area open to juvenile fish now becomes limited leading to a disproportionate effect on selectivity. Square mesh netting is one accepted way of changing size selectivity in codends and extensions. If set correctly, this mesh is not liable to distort when subjected to changes in dynamic loading thus allowing a constant opening for the escape of small fish species.

The United Kingdoms' Sea Fish Industry Authority (Seafish), the Scottish Fisheries Research Service at the Marine Laboratory, Aberdeen (FRS-MLA) and the Department of Agriculture of Northern Ireland (DANI) have been testing square mesh selector panels since 1989. With the aim of reducing discards of haddock, whiting and cod from whitefish trawls, trials concentrated predominantly in the North Sea (Arkley, 1990; 1991). To an effect, the use of square mesh has been relatively successful leading to its further use in the *Nephrops* fishery in the Irish Sea and the North Sea (Arkley, 1993a,b; Briggs and Robertson, 1993).

In 1992, further trials with square mesh panels were carried out off the English coast in ICES areas VIIe and VIIf (Arkley, 1992). The aim was to reduce discards in a multi-species fishery using a single boat demersal trawler. The results indicated discard reductions for whiting and hake but fishermen expressed concern at losses of marketable fish species such as squid and red mullet.

The Irish Sea Fisheries Board (BIM) have been carrying out industry led trials with square mesh selector panels since November 1990. The research was aimed at reducing whiting and juvenile hake discards in the *Nephrops* fisheries within the Irish Sea (Rihan and McCormack, 1990; Hillis *et al.*, 1991) and was later extended to the smaller fishery in both the Celtic Sea and south coast of Ireland (Rihan, 1992a; 1993a). Overall, the work demonstrated that with careful selection of mesh size considerable reductions of non-target and juvenile fish species could be achieved. Further trials in 1993 indicated that the "sieving" effect of large mesh panels on the bottom sheet of conventional trawls reduced the catches of bottom debris and unwanted finfish and shellfish species. Similarly designed large mesh bottom sheets panels were utilised off the west coast of Ireland with monkfish, megrim and hake. Positive results were experienced but in mixed flatfish fisheries discard reductions were at the expense of marketable sole (Rihan, 1992b, 1993b).

Overall, the research indicated that square mesh can narrow the selection range for any one species of fish but do not provide an appropriate solution to the problems presented by a mixed species fishery.

2.3.3 Codend modifications

The influence of codend geometry and construction on selectivity processes has been recognised for at least two hundred years. Holt (1895), reported that square mesh in codends "caught considerably less small fish than an ordinary codend with mesh of the same size...". A long tradition of research has included codend modifications in round, flat fish, crustacean and pelagic fisheries. As a general observation, most of the reported research has shown good conservation potential with the techniques either being incorporated into management legislation or adopted voluntarily by fishermen because they offer clear operational benefits.

2.3.3.1 Square mesh codends

Within the U.K. research has been undertaken by FRS-MLA on the use of square mesh codends in demersal trawls. Experiments were carried out on both chartered commercial and research vessels with cod, whiting and haddock being the main target species (Armstrong *et al.*, 1989; Cooper *et al.*, 1989; Robertson and Shanks, 1989). While the results indicated a number of benefits in terms of selectivity, some limitations of the square mesh sections also became apparent. Reduced strength of the square mesh was identified, as was knot slippage, both a result of the way that the standard netting had simply been turned through 45° to take up a square configuration.

The Norwegian Institute of Fishery Technology Research (IFTR) found high selection factors and 50% retention lengths for cod and haddock when square mesh codends were tested. Selective properties of the square mesh were reduced, however, in the red fish (*Sebastes marinus*) fishery due to a high degree of meshing for that species. The reduced elasticity of square mesh also lead to handling problems (Isaksen and Valdermarsen, 1986; Karlsen, 1986; ; Karlsen and Larsen, 1988; Larsen, 1988).

Comparative selectivity trials were also carried out in Germany using diamond and square mesh codends with the selectivity of the target species i.e. redfish and cod, being improved. However, when square mesh codends were evaluated in the saithe fishery, in contrast with other gadoids, no change in selectivity characteristics were noted (Lange, 1992; Thiele, 1994). The effect of square mesh on the benthos has not been reported, but it is reasonable to suspect that unobstructed openings of square mesh will allow more benthos to pass through this section of the trawl than occluded openings, thereby reducing the amount of invertebrate bycatch. Consequences for mortality of invertebrates in the trawltrack are not yet known.

2.3.3.2 Codend separator panels

Experiments with codend separator panels used to catch mixed white fish species have been undertaken in the U.K. involving MAFF, FRS-MLA, the National Federation of Fishermen's Organisations and Seafish. A separator trawl was fitted with a 120 mm lower codend and compared to that of a standard 100 mm codend net. The target species in the areas fished were cod, haddock, whiting, lemon sole and plaice. The results appeared encouraging with the separator trawls showing a useful reduction in catches of sub-legal fish as well as size grades around the minimum legal size (Main and Sangster, 1990; Sangster *et al*., 1990). Behavioural similarities made it extremely difficult to segregate cod from flatfish species however.

2.3.3.3 Codend Geometry

In addition to conventional modifications, experiments have been undertaken to manipulate selectivity by changing relative dimensions of codends and their associated extension pieces. One such method is the use of shortened selvage ropes. A relatively recent innovation, these ropes work by relieving diamond meshes of much of the force that would normally act to close them. This is done by setting the netting onto "frame" ropes that are often present to give extra strength to the structure.

In Norway, the selectivity level of the codend was significantly increased when the selvedge rope was shortened by 12-15 % (Isaksen and Valdermarsen, 1990). Similarly, the Marine Laboratory based in Aberdeen, using shortened selvedge ropes in *Nephrops* trawls achieved selectivity levels comparable to those achieved for square mesh codends (Stewart and Galbraith, 1989; Stewart, 1990).

Alterations to codend dimensions have also been shown to affect fish selectivity. In Scotland this has concentrated on the length of the extension piece, the diameter of the codend and the number of meshes in the codend circumference.

Trials directed by FRS-MLA demonstrated that selectivity could be significantly affected by varying these design features (Robertson and Shanks, 1989). In particular, it was discovered that long extension pieces create a narrow tube with closed meshes. Large numbers of meshes in the codend circumference produce a similar barrier to escape. These results lead to the design of the Armstrong Linear Model which is currently used in conservation legislation to describe the influence of the main factors determining codend selectivity i.e. mesh size, codend diameter and extension length (Stewart and Galbraith, 1989).

2.3.4. Netting Material

Recent years has seen development in the materials used for trawl net manufacture. Conventionally, square mesh panels were constructed from diamond mesh material mounted on the square. This has given way however to knotless material in braided Polyamide (PA) or Polyethene (PE) which has a number of advantages over knotted material. It maintains a regular "square" shape whereas knotted material is susceptible to knot slippage. Knot absence also reduces abrasion damage to escaping fish and generally improves the escape area.

Despite these obvious advantages a number of drawbacks still exist with this material. Given that square mesh panels will undoubtedly have to be replaced over time a secure supply of cost effective material will have to be obtained. In addition, knotless material cannot be repaired using the conventional method and mending can therefore be time consuming.

2.3.5. Roller Ball modification

One of the latest gear modifications to be tested is a series of weighted rollers on the groundrope, replacing the rubber ground rope or bobbins of a standard ottertrawl (Ball *et al.*, 1999). The aim of this design is to allow the trawl to move over, rather than through, the seabed. The action of the rollers appears to stimulate fish to rise from the seabed, negating the requirement for tickler chains.

2.3.5.1 Consequences for commercial catch

The system is currently in the development phase, but preliminary trials indicate no reduction in commercial catch. It would appear, however, that as the trawl is not penetrating the seabed to the same degree as the standard gear, the catch is cleaner and contains less debris. Due to the reduction in hauling force, there is some indication that fuel consumption may be reduced.

2.3.5.2 Consequences for Seabed

Not yet tested.

2.3.5.3 Consequences for non-target fish mortality

No significant difference.

2.3.5.4 Consequences for invertebrate mortality

As yet unknown, but it is anticipated that a reduction in invertebrate mortality will be achieved due to the trawl passage being over, rather than through, the seabed.

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REFERENCES

Agricola, J.B., 1985. Experiments on electrical stimulation of flatfish in beam trawling during 1984. ICES C.M. 1985/B:36.

Anon., 1973. Effects of trawls and dredges on the sea bed. ICES C.M. 1973/B:2 Gear and Behaviour Committee, 4 pp.

Anon., 1988. Report of the study group on the effects of bottom trawling. ICES C.M. 1988/B: 56. Fish Capture Committee, 30 pp.

Anon., 1996. Report of the working group on the ecosystem effects of fishing activities. ICES C.M. G:1, 131 pp.

Arkley, K., 1990. The use of square mesh selector panels as a means of improving selectivity of demersal towed fishing gears. rv "CLUPEA" mfv "KESTREL" and mrv "ST. KILDA". Sea Fish Industry Authority Report No. 378, 26 pp.

Arkley, K., 1991. Square mesh selector panels as a means of improving selectivity of demersal towed fishing gears-A summary of the work carried out by the gear technology group 1989/90. Sea Fish Industry Authority Report No. 384, 39 pp.

Arkley, K., 1992. ICES area VIIf selectivity trials single boat demersal trawl-MFV Our Ocean Harvester (PZ403). Sea Fish Industry Authority Report No. 406, 24 pp.

Arkley, K., 1993a. Fishing trials to evaluate the use of square mesh selector panels fitted to *Nephrops* trawls-MFV Heather Sprig (BCK 181). Sea Fish Industry Authority Report No. 383, 21 pp.

Arkley, K., 1993b. Improvement of selectivity of demersal trawl gear-positioning of square-mesh selection panels in *Nephrops* trawls. Sea Fish Industry Authority Report No. 422, 68 pp.

Armstrong, D.W., Fryer, S.A., Coull, K.A., 1989. Codend selectivity of cod, haddock and whiting by Scottish trawlers and seiners. ICES Council meeting 1989. ICES CM 1989/B:55.

Arntz W. & W. Weber (1970) *Cyprina islandica* (Mollusca: Bivalvia) als Nahrung von Dorsch und Kliesche in der Kieler Bucht. Berichte der Deutschen Wissenschaftlichen Kommission für Meeresforschung 21, 193-209.

Auster, P.J., Malalesta, R.J., Langton, R.W., Watling, L., Valentine, P.C., Donaldson C.L.S., Langton, E.W., Shepard, A.N., Babb, I.G., 1996. The impact of mobile fishing gear on seafloor habitats in the Gulf of Maine (Northwest Atlantic). Implications for conservation of fish populations. Review Fisheries Science 4, 185-202.

Baker, C., 1973. Experimentary electric fishing voyage on DAFS research vessel, Clupea. White Fish Authority (WFA) FR 066.

Ball, B., Munday, B., Fox, G. 1999. The impact of a *Nephrops* otter trawl fishery on the benthos of the Irish Sea. *Journal of Shellfish Research*, 18 (2):708.

BEON, 1991. Effects of beamtrawl fishery on the bottom fauna in the North Sea. II - The 1990 studies. BEON - report 13, 85 pp.

Bergman, M.J.N., Fonds, M., Hup, M., Lewis, W., van der Puyl, P., Stam, A., den Uyl, D., 1990. Direct effects of beamtrawl fishing on benthic fauna in the North Sea-a pilot study. In: Effects of beamtrawl fishery on the bottom fauna of the North Sea. BEON-rapport 8, 33-57.

Bergman, M.J.N., Ball, B., Bijleveld, C., Craeymeersch, J.A., Munday, B.W., Rumohr, H., van Santbrink, J.W., 1998. Direct mortality due to trawling. In: H.J. Lindeboom and S.J. de Groot (Editors), Impact-II. The effects of different types of fisheries on the North Sea and Irish Sea benthic ecosystems. NIOZ-Rapport 1998-1/RIVO-DLO Report CO 03/98, 167-184 pp.

Bergman, M.J.N., Hup, M., 1992. Direct effects of beam trawling on macrofauna in a sandy sediment in the southern North Sea. ICES Journal of Marine Science 49, 5-11.

Bergman, M.J.N., van Santbrink, J.W., in press. Fishing mortality in megafaunal populations due to trawling in the southeastern North Sea. ICES Journal of Marine Science.

Blaber, S.J.M., Wassenberg, T.J., 1989. Feeding ecology of the piscivorous birds *Phalocrocorax varius*, *P. melanoleucos* and *Sterna bergii* in Moreton Bay, Australlia: diets and dependence on trawler discards. Marine Biology 101, 1-10.

Blom, W.C., 1990. Some remarks about the beam trawl. In: Effects of beam trawl fishery on the bottom fauna in the North Sea. BEON report 8: 26-31

Boesch, D.F., Rosenberg, R., 1981. Response to stress in marine benthic communities. In: G.W. Barrett and R. Rosenberg, (Editors). Stress effects on natural ecosystems, pp. 179-200. New York, J. Wiley and Sons.

Bridger, J.P., 1970. Some effects of the passage of a trawl over the seabed. ICES C.M. 1970/B:10.

Bridger, J.P., 1972. Some observations on the penetration into the sea bed of tickler chains on a beam trawl. ICES C.M. 1972/B:7. Gear and Behaviour Committee, 9 pp

Briggs, R.P., Robertson, J.H.B., 1993. Square mesh panel studies in the Irish Sea *Nephrops* fishery. ICES, CM/B:20, 10 pp.

Caddy, J.F., 1973. Underwater observations on tracks of dredges and trawls and some effects of dredging on a scallop ground. Journal of the Fisheries Research Board of Canada 30, 173-180.

Camphuysen, C.J., Ensor, K., Furness, R.W., Garthe, S., Huppop, O., Leaper, G., Offringa, H., Tasker, M.L., 1993. Seabirds feeding on discards in winter in the North Sea. Netherlands Institute for Sea Research, Den Burg, Texel. NIOZ-Rapport 1993-8, 142 pp.

Clerck R. de, Hovart, P., 1972. On the effects of tickler chains. ICES, C.M. 1972/B:15, 11 pp.

Connell, J.H., 1978. Diversity in tropical rain forests and coral reefs. Science 199, 1302-1310.

Cooper, C., Hickey, W., Walsh, S.J., 1989. Size selection of plaice by square and diamond mesh codends. ICES CM 1989/B:22, 13pp.

Craeymeersch, J.A., Ball, B., Bergman, M.J.N., Damm, U., Fonds, M., Munday, B.W., Rumohr, H., van Santbrink, J.W., 1998. Catch efficiency of commercial trawls. In: H.J. Lindeboom and S.J. de Groot (Editors), Impact-II. The effects of different types of fisheries on the North Sea and Irish Sea benthic ecosystems. NIOZ-Rapport 1998-1/RIVO-DLO Report C003/98, 18-23 pp.

Creutzberg, F., Duineveld, G.C.A., van Noort, G.J., 1987. The effect of different numbers of tickler chains on beam trawl catches. Journal du Conseil International pour l'Exploration de la Mer 43, 159-168.

Daniulyte, G., Petrauskiene, L., 1987. Anode electrotaxis of fishes of various ecological groups with respect to their locomotion mode and its mechanism. Acta Hydrobiologica Litunica, Volume 6, ISSN 0208-2527, 20-27.

Daniulyte, G., Naktinis, J.,Petrauskiene, L., 1987. Dependence of anode electrotaxis efficiency of marine fishes on pulse current parameters. Acta Hydrobiologica Litunica, Volume 6, ISSN 0208-2527, 3-11.

Evans, S.M., Hunter, J.E., 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: S.J. de Groot and H.L. Lindeboom (Editors), 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.

Fonds, M., Blom, W., 1996. Onderzoek naar de mogelijkheden tot vermindering van discardproduktie door technische aanpassing van boomkornetten. BEON rapport nr. 96-15, pp 30.

Fonds M., Groenewold, S., 2000. Food subsidies generated by the beam-trawl fishery in the southern North Sea. In: M.J. Kaiser and S.J. Groot de (Editors.) Effects of fishing on non-target species and habitats. Blackwell Science: 130-150.

Fonteyne, R., Ball, B., Kujawski, T., Munday, B.W., Rumohr, H. Tuck, I., 1998. Physical Impact. In: H.J. Lindeboom and S.J. de Groot (Editors), Impact-II. The effects of different types of fisheries on the North Sea and Irish Sea benthic ecosystems. NIOZ-Rapport 1998-1/RIVO-DLO Report CO 03/98, 120-156 pp.

Fox, G.M., Ball, B.J., Munday, B.W., Pfeiffer, N., 1996. The IMPACT II study: preliminary observations on the effects of bottom trawling on the ecosystem of the *Nephrops* grounds in the N.W. Irish Sea. In Irish Marine Science 1995, pp 337-354. Ed. by B.F. Keegan and R. O'Conner. Galway University Press Ltd., Galway, 626 pp.

Garthe S., Camphuysen, K., Furness, R., 1996. Amounts of discards by commercial fisheries and their significance as food for seabirds in the North Sea. Marine Ecology Progress Series 136, 1-11.

Graham, M., 1955. Effect of trawling on animals of the sea bed. Papers in Marine Biology and Oceanography, Suppl. to Vol. 3 of Deep Sea Research, 1-6 pp.

Grassel, J.F., Saunders, H.L., 1973. Life histories and the role of disturbance. Deep Sea Research 20, 643-659.

Groot, S.J. de, 1972. Some further experiments on the influence of the beam trawl on the bottom fauna. ICES C.M. 1972/B:6, 7 pp.

Groot, S.J. de, 1984. The impact of bottom trawling on benthic fauna of the North Sea. Ocean Management 9, 177-190.

Groot, S.J. de, 1995. On the penetration of the beam trawl into the sea bed. ICES C.M. 1995/B:36. Fish Capture Committee.

Groot, S.J. de, Apeldoorn, J., 1971. Some experiments on the influence of the beam trawl on the bottomfauna. ICES C.M. 1971/B:2.

Groot, S.J. de, Boonstra, G.P., 1970. Report on the development of an electrified shrimp-trawl in The Netherlands. ICES C.M. 1970/B:5

Groot, S.J. de, Lindeboom, H.J., 1994. Environmental impact of bottom gears on benthic fauna in relation to natural resources management and protection of the North Sea. pp. NIOZ-Rapport 1994-11/RIVO-DLO Report CO 26/94, 257 pp.

Hall, S.J., 1994. Physical disturbance and marine benthic communities: life in unconsolidated sediments. Oceanography and Marine Biology Annual Review 32, 179-239.

Hill, B.J., Wassenberg, T., 1990. Fate of discards from prawn trawlers in Torres Strait. Australian Journal of Marine and Freshwater Research 41, 53-64.

Hillis, J.P., McCormick., R., Rihan, D., Geary, M., 1991. Square mesh experiments in the Irish Sea. ICES C.M. 1991/B:58, 7pp.

Holme, N.A., 1983. Fluctuations in the benthos of the western English Channel. Oceanological Acta, Proceedings 17th EMBS, Brest, France, 121-124.

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).

Horn, W., 1976. Rationalization of sole fisheries by means of electrified beam trawls. In: Coun. Meet. ICES/B: 7. Report of the Working Group on Research on Engineering Aspects of Fishing Gear, Vessels and Equipment.

Houghton, R.G., Williams, T., Blacker, R.W., 1971. Some effects of double beam trawling. ICES C.M. 1971/B: 5. Gear and Behaviour Committee.

Isaksen, B., Valdermarsen, J.W., 1986. Selectivity experiments with square mesh codends in bottom trawls, ICES CM. 1986/B: 28, 9pp.

Isaksen, B., Valdermarsen, J.W., 1990. Codend with short lastridge ropes to improve selectivity in fish trawls. ICES CM. 1990/B: 46.

Jones, J.B., 1992. Environmental impact of trawling on the sea-bed: a review. New Zealand Journal of Marine and Freshwater Research 26, 59-67.

Karlsen, K., 1986. Fishing experiments with square mesh codends in Norwegian shrimp trawls. ICES Fish. Technol. Fish. Behav. WG. Hull, May, 1986.

Karlsen, L., Larsen, R., 1988. Progress in the selective shrimp trawl development in Norway. In: Proceedings of the World Symposium on Fishing Gear and Fishing Vessel Design. The Newfoundland and Labrador Institute of Fisheries and Marine Technology, St. Johns, Newfoundland, Canada. 30-38 pp.

Kazlauskiene, N., 1987. DC effect on the heart rhythm of fishes. Acta Hydrobiologica Litunica, Volume 6, ISSN 0208-2527, 54-68.

Kazlauskiene, N., Daniulyte, G., 1987. Effect of DC on ECG of fishes. Acta Hydrobiologica Litunica, Volume 6, ISSN 0208-2527: 53-60.

Khandriche, A., Werner, F., Erlenkeuser, H., 1986. Auswirkungen der Oststürme vom Winter 1978/1979 auf die Sedimentation im Schlickbereich der Eckernförder Bucht (westlichr Ostee). Meyniana 38, 125-152.

Krost, P., 1990. The impact of otter-trawl fishery on nutrient release from the sediment and macrofauna of Kieler Bucht (Western Baltic). Berichte aus dem Institut für Meereskunde an der Christian-Albrechts-Universität, Kiel. Nr. 200: 157 pp (in German, English summary).

Krost, P., Bernhard, M., Werner, F., Hukriede, W., 1990. Otter trawl tracks in Kiel Bay (Western Baltic) mapped by side-scan sonar. *Meeresforschung* 32, 344-354.

Laane, R. et al., 1990. De zee, de zee de Noordzee. Ministry of Transport and Public Works. Tidal Water Division, 194 pp.

Laban, C., 1992. Penetration depth of beam trawl gear. In: Effects of beam trawl fishery on the bottom fauna in the North Sea III - The 1991 studies. BEON Report 16, 23-24

Laban, C., Lindeboom, H.J., 1991. Penetration depth of beam trawl gear. In Effects of beam trawl fishery on the bottom fauna in the North Sea: the 1990 studies. BEON report 13, 37-52.

Lange, K., 1992. Selektionversuche mit Trenngittern. Infn Fischw 39, 164-165.

Larsen, R.B., 1988. A review of the application and selectivity of square mesh netting in trawls and seines: Investigations into the selectivity of square mesh in bottom trawls. Div. Mar. Fish., Mass. USA, Dept. Fish & Oceans, Canada, N. England Mar Fish. Council, U.S.A. Workshop on Square Mesh, Nov. 1988.

Lart, W.J., Horton, R.S., 1996. Electric Fishing: Environmental Perspectives on Seafish and White Fish Authority Work Sea Fish Industry Authority-Technology Division Confidential Report No. 96.

Lindeboom H.J., Groot, S.J. de (editors), 1998. The effects of different types of fisheries on the North Sea and Irish Sea benthic ecosystems. IMPACT-II Report. Chapters 2. Materials and Methods, and 3. Results; Ottertrawls - Immediate effects pp. 19, 126-127.

Main, J., Sangster, G.I., 1978. The value of direct observation techniques by divers in fishing gear research. Scottish Fisheries Research Report No. 12, Dept. of Agriculture and Fisheries for Scotland, Aberdeen Scotland, 15 pp.

Main, J., Sangster, G.I., 1981. A study of sand clouds produced by trawl boards and their possible effect on fish capture. Scottish Fisheries Research Report No. 20, Dept. of Agriculture and Fisheries for Scotland, Aberdeen Scotland, 19 pp.

Main, J., Sangster, G.I., 1990. An assessment of the scale damage to and survival rates of young gadoid fish escaping from the cod-end of a demersal trawl. Scottish Fisheries Research Report, 46.

Malkevicius, S., 1977. The main points of the method of calculation of pulse generators for electric fishing. ICES C.M. 1977/B:16.

Margetts, A.R., Bridger, J.P., 1971. The effect of a beam trawl on the sea bed. ICES C.M. 1971/B:8, 9 pp.

Messieh, S.N., Rowell, T.W., Peer, D.L., Cranford, P.J., 1991. The effects of trawling, dredging and ocean dumping on the eastern Canadian continental shelf seabed. Continental Shelf Research 11, 1237-1263.

Pauly, D., Christensen, V., 1995. Primary production required to sustain global fisheries. Nature, 374, no. 6519, 255-257.

Rauck, G., 1985. Wie schädlich ist die Seezungebaumkurre für Bodentiere? Inf. f.d. Fischwirtschaft 1985, Heft 4.

Rauck, G., 1988. Ecological consequences of dredging and bottom trawling in the Limfjord, Denmark. Marine Ecology Progress Series 69, 171-178.

Rihan, D., McCormack, R., 1990. Square mesh trials in the Irish Sea Nov-Dec 1990. BIM Internal Report, 16 pp.

Rihan, D., 1992a. Square mesh selectivity trials off the South Irish Coast mfv "SYLVIE LYDIE", Dunmore East, July 1992. BIM Internal Report, 6 pp.

Rihan, D., 1992b. Square mesh selectivity trials off the North West Coast mfv "JANIREH", Killybegs. BIM Internal Report, 5 pp.

Rihan, D., 1993a. Square mesh selectivity trials off the South Irish Coast mfv "CARONA II", June-July 1993. BIM Internal Report, 5 pp.

Rihan, D., 1993b. Preliminary flatfish selectivity trials off the North West Coast mfv "JANIREH", Killybegs August, 1993. BIM Internal Report, 7 pp.

Robertson, J.H.B., Shanks, A.M., 1989. Further studies on the size selection of *Nephrops* by different codends. Department of Agriculture and Fisheries for Scotland. Scottish Fisheries Working Paper 1/89: 1989.

Sangster, G.I.., Main, J., Shanks, A.M., 1990. Twin trawling trials to obtain catch comparison data between a standard dual purpose fish/prawn net and the same net fitted with a separator panel. Dept. of Agriculture and Fisheries for Scotland. Scottish Fisheries working Paper No. 4/90.

Santbrink, J.W. van, Bergman, M.J.N., 1994. Direct effects of beam trawling on macro-fauna in a soft bottom area in the southern North Sea. In: Environmental impact of bottom gears on benthic fauna in relation to natural resources management and protection of the North Sea (editors S. J. de Groot and H. J. Lindeboom). NIOZ-Report 1994-1, RIVO-DLO Report CO26/94, 147-178 pp.

Schwinghamer, P., Guignè, J.Y., Siu, W.C., 1996. Quantifying the impact of trawling on benthic habitat structure using high resolution acoustics and chaos theory. Canadian Journal of Fisheries and Aquatic Sciences 53, 288-296.

Simonaviciene, B., 1987. Pulse current stress effect on gold-fish feeding conditioned reflexes. Acta Hydrobiologica Litunica, Volume 6, ISSN 0208-2527, 37-46.

Stewart, P.A.M., 1972. The selection of electrode materials for electrical fishing. SOAFD Marine Lab. Aberdeen. No. IR 72-1. Unpublished typescript.

Stewart, P.A.M., 1979. A study of the response of flatfish (Pleuronectidae) to electrical stimulation. J. Cons. int. Explor. Mer., 37(2), 123-129.

Stewart, P.A.M., Galbraith, R.D., 1989. Codend Design, Selectivity and Legal Definitions. Int. Coun. Explor. Sea, CM/B: 11, 7 pp.

Stewart, P.A.M., 1990. How rigging codends changes selectivity. Fishing News. 1990.

Sydow, J.S., 1990. Cruise report experiments on the interaction fishing gear (beamtrawl)-benthos with the R.V. MITRA. In Effects of beamtrawl fishery on the bottom fauna of the North Sea. BEON-rapport 8, 7-21.

Thiele, W., 1994. Einsatz von Sortiergittern. Infn Fischw. 41, 41-46.

Tuck, I., Ball, B., Schroeder, A., 1998. Comparison of undisturbed and disturbed areas. In: H.J. Lindeboom and S.J. de Groot (Editors), Impact-II. The effects of different types of fisheries on the North Sea and Irish Sea benthic ecosystems. NIOZ-Rapport 1998-1/RIVO-DLO Report CO 03/98.

Van Marlen, B., 1985. Report of a seminar on electro-fishing at RIVO-IJmuiden on 24 January 1985. ICES C.M. 1985/B:37.

Vanden Broucke, G., 1973. Verder onderzoek over het electrisch vissen. Mededelingen van het Rijksstation voor Zeevisserij, 85-TZ/56/1973.

Vosyline, M., 1987. Effect of electric current on some physiological parameters of rainbow trout. Acta Hydrobiologica Litunica, Volume 6, ISSN 0208-2527, 47-52.

Wassenberg, T., Hill, B., 1990. Partitioning of material discarded by prawn trawlers in Moreton Bay. Australian Journal of Marine and Freshwater Research 41, 27-36.