Aquat. Living Resour. 14 (2001) 283−291

S0990744001011354/FLA

Fish bycatch and discarding in *Nephrops* trawlers in the Firth of Clyde (west of Scotland)

Yorgos Stratoudakis, Robert J. Fryer*, Robin M. Cook, Graham J. Pierce, Ken A. Coull

FRS Marine Laboratory, Victoria Road, Aberdeen AB11 9DB, Scotland, UK

Received 13 September 2000; accepted 16 July 2001

Abstract − *Nephrops norvegicus* (Norway lobster or prawn) is an important target species in demersal fisheries of the north-east Atlantic. Trawling for *Nephrops* is wasteful when many small fish are caught and discarded in the process. Here, data from 106 commercial fishing trips, sampled between 1982 and 1998 as part of the Scottish discard sampling programme, are used to investigate the fish bycatch and discards of *Nephrops* trawlers in the Firth of Clyde (west of Scotland). A large proportion of the fish caught in the Clyde is discarded, the discards mainly consisting of small demersal fish (mean length about 19 cm), particularly young whiting (*Merlangius merlangus*). Within the study period, annual estimates of total fish discards ranged from 318 to 3 027 tonnes, with a mean of 1 761 tonnes. Fish landings and discards biomass per unit effort both decreased over the study period. However, the decline in landings per unit effort was greater than that in discards per unit effort, corresponding to an increase in the discard rate over time. In recent years, discards have comprised about 70 % of the fish bycatch. The mean length of discarded fish was positively related to mesh size. © 2001 Ifremer/CNRS/Inra/IRD/Cemagref/Éditions scientifiques et médicales Elsevier SAS

bycatch / fish discards / trawling / *Nephrops norvegicus* / Firth of Clyde

Résumé − Captures accessoires et rejets des chalutiers pêchant la langoustine dans le golfe de la Clyde (ouest-Écosse). La langoustine *Nephrops norvegicus* est une espèce importante dans les captures démersales de l'Atlantique nord-est. Le chalutage des langoustines peut entraîner le gaspillage de nombreux poissons de petites tailles qui sont capturés en même temps. Ici, des données provenant de 106 campagnes de pêche commerciale, échantillonnées de 1982 à 1998 dans le cadre du programme d'échantillonnage des rejets écossais, sont utilisées pour étudier les captures accessoires et les rejets des chalutiers pêchant la langoustine dans le golfe de la Clyde (ouest-Écosse). Une grande proportion de ces poissons capturés sont rejetés ; ces rejets consistent principalement en poissons démersaux de petites tailles (longueur moyenne de 19 cm environ), en particulier de jeunes merlans (*Merlangius merlangus*). Dans la période étudiée, l'évaluation annuelle de la totalité des rejets est comprise entre 318 et 3 027 tonnes, avec une moyenne de 1 761 tonnes. Les débarquements de poisson, ainsi que la biomasse des rejets par unité d'effort diminuent tout au long de la période étudiée. Cependant, ce déclin en débarquement par unité d'effort est plus élevé que celui des rejets par unité d'effort, correspondant à une augmentation du taux de rejet. Ces dernières années, les rejets représentaient environ 70 % des captures accessoires. La longueur moyenne des poissons rejetés est proportionnelle à la maille du filet. © 2001 Ifremer/CNRS/Inra/IRD/Cemagref/Éditions scientifiques et médicales Elsevier SAS

captures accessoires / rejets / chalutage / *Nephrops norvegicus* / Firth of Clyde

1. INTRODUCTION

Trawling for *Nephrops norvegicus* (also known as the Norway lobster or prawn) is an important fishing activity around Scotland. In the past decade, the annual value of *Nephrops* landed in Scottish harbours has exceeded £30 million (50 million Euros) at first sale, almost 10 % of the total value of all fish and shellfish landed in Scotland. *Nephrops* are mainly targeted by small demersal trawlers of less than 30 m that are allowed to use smaller meshed cod-ends than whitefish vessels provided that *Nephrops* constitute a certain minimum proportion by weight of the total landings (Bailey et al., 1986; Tuck et al., 1997). The

**Correspondence and reprints:* fax: + 44 1224 295511.
E-mail address: R.Fryer@marlab.ac.uk (R.J. Fryer).

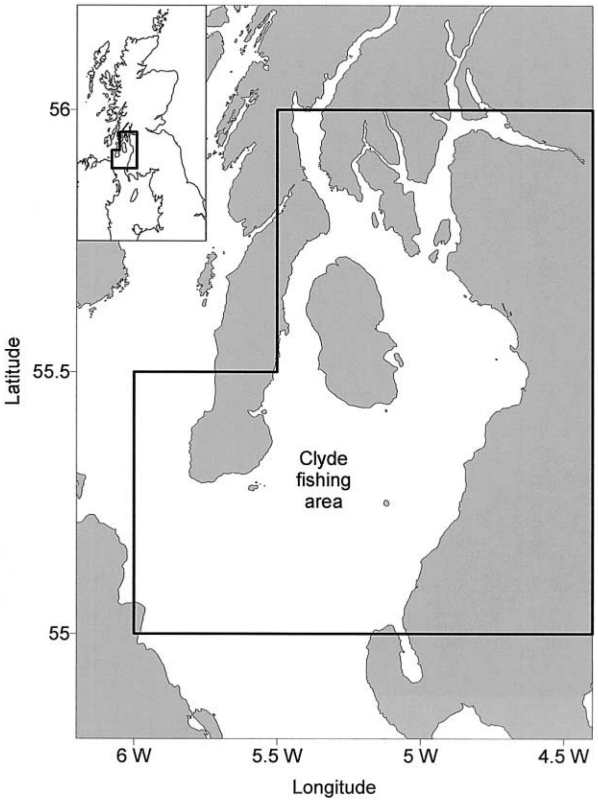

Figure 1. The Firth of Clyde in the west of Scotland. There are various definitions of the Clyde fishing area, depending on which stock is being assessed. Here, we use the area used for *Nephrops* assessments, delineated by the thick black lines.

use of smaller mesh can result in the bycatch of large quantities of fish (Briggs, 1985; Evans et al., 1994; Liggins et al., 1996), much of which (in Scotland) is discarded to satisfy minimum landing size regulations and to reduce the proportion of fish in the total landings.

The distribution of *Nephrops* is generally limited by the availability of suitable particulate sediment. The Firth of Clyde (*figure 1*) is a relatively isolated area in the west of Scotland where the patterns of water circulation produce sediment types that favour the burrowing behaviour of *Nephrops* (Bailey et al., 1986). Over the last 20 years, trawling for *Nephrops* has become the most important fishing activity in the Clyde. Recently, more than 90 % of the trawling activity in the Clyde has been targeted towards *Nephrops*, and the Clyde *Nephrops* fishery has accounted for more than 20 % of the total *Nephrops* biomass landed in Scotland (unpublished records of the Scottish Executive Environment and Rural Affairs Department, SEERAD). The regulations governing trawling in the Clyde are quite complicated, and those in force up to 31 December 1999 are summarised in *table I*.

Several studies have concentrated on the biology and catches of *Nephrops* in the Clyde (Bailey et al., 1986; Tuck et al., 1997). However, there is currently little information on fish landings by Clyde *Nephrops* trawlers (Hislop, 1986), and the only information on fish discards is a recent study that followed the composition and fate of discards from Clyde *Nephrops* trawlers through a calendar year (Wieczorek et al., 1999). Here, we use observations from the Scottish discard sampling programme to describe the bycatch and discarding of fish in the Clyde *Nephrops* trawl fishery. The analysis is based on data from 106 fishing trips sampled by scientific observers between 1982 and 1998. In particular, we summarise the species composition, size distribution, and biomass of the fish discards, and estimate the total biomass of fish discarded annually in the fishery. The estimates of annual fish discards are compared with official annual landings of fish and *Nephrops* and with estimates of total *Nephrops* discards.

We also use the data to investigate how three summary measures of fish bycatch (the number of species discarded, the mean length of discards, and the total bycatch biomass per unit effort) vary over time, with quarter, and with mesh size. A particular advantage of the data set is that, partly due to the regulations in *table I*, vessels with 70- and 80-mm mesh size were sampled throughout the study period, allowing relationships with mesh size to be explored under commercial fishing conditions. Previous studies have generally been under experimental conditions, with emphasis placed on the species with the highest commercial interest (Briggs, 1992; Armstrong et al., 1998; Briggs et al., 1999).

Table I. Summary of regulations governing trawling in the Clyde up to 31 December 1999.

Trawl	Minimum mesh size	Landing restrictions (in addition to minimum landing size regulations)
Single-rig	70 mm	Landings must comprise at least 30 % by weight of *Nephrops* and at most 60 % of protected fish species (Anon., 1980).
Single- or multiple-rig	80 mm	None

80-mm square mesh panel mandatory in the top sheet since 1992.
Classified by SEERAD (Scottish Executive Environment and Rural Affairs Department) as a *Nephrops* trawler if landings comprise at least 30 % by weight of *Nephrops*, regardless of mesh size.

2. MATERIALS AND METHODS

2.1. The Scottish discard sampling programme

Regular discard sampling by scientific observers onboard UK vessels fishing around Scotland began in 1975 and continues to the present day (Jermyn and Robb, 1981; Stratoudakis, 1997). The main objective of the programme is to provide annual estimates of the numbers of fish discarded, which are then used in the assessment of the haddock (*Melanogrammus aeglefinus*) and whiting (*Merlangius merlangus*) stocks in the North Sea and the west of Scotland (Stratoudakis et al., 1999). An additional objective is to collect discard information for fish species with limited or no commercial interest (Stratoudakis, 1997). Co-operation by fishing vessels is on a voluntary basis.

Discard sampling of *Nephrops* trawlers in the Clyde began in 1982, and is based on stratified random sampling by quarter within each year. Specifically, one vessel is sampled each quarter, with the observer monitoring fish discards and landings over several consecutive days. During this 'visit' to the fishery, the vessel can make several 'trips', i.e. periods spent away from harbour until returning to land. There were sixty visits between 1982 and 1998 (not all quarters were sampled), each comprising one to three trips over 1–5 d.

On each visit, detailed information is collected about fish discards, including length frequencies for all discarded fish species by haul. The total weight of fish discarded is then estimated using species-specific length-weight relationships (Coull et al., 1989). Only limited information is collected about fish landings, and here we restrict attention to the biomass of whiting, hake and total demersal fish landings on each visit. Since demersal fish generally form the bulk of the fish landings, we refer to fish landings and demersal fish landings interchangeably. Unfortunately, for practical reasons, data on *Nephrops* discards in Scottish fisheries have been collected under a separate sampling programme, so simultaneous analysis of fish and *Nephrops* discards is not possible.

It is important to recognise some limitations in the data. Although vessels are nominally sampled at random, vessels are actually selected for pragmatic reasons: they must be large enough to accommodate an observer, willing to co-operate, and accessible at the time of the visit. A consequence is that the sampled vessels are larger than average and tend to land about three times more fish per trip than the reported fleet average (unpublished SEERAD records). Therefore, to use the discard data, we must assume that the species composition of the catch and the discard rates of the sampled vessels are typical of the fleet (although the absolute quantities both landed and discarded are not). We have no means of verifying this assumption, but we examine the likely impact on our results if this assumption breaks down. Note that the scientific observers have considerable experience and are convinced that their presence does not change the fishermen's behaviour. Indeed, when the discard programme was first established, the landings of the monitored vessel from unobserved trips were also sampled, without the knowledge of the crew. These were compared to the landings from the observed trips and revealed no detectable change in behaviour (S. Jermyn, FRS Marine Laboratory Aberdeen, pers. comm.).

2.2. Estimation of total annual fish discards

The total fish biomass discarded annually in the Clyde *Nephrops* fishery was estimated using the 'collapsed ratio estimator' developed by Stratoudakis et al. (1999). Traditionally, total annual discards have been estimated by applying a ratio estimator to the data from each stratum (i.e. each quarter) and then summing across strata. However, Stratoudakis et al. (1999) showed that when there is little replication within strata (as here), these estimators can be very biased and variable. Further, they showed that collapsing the stratification into groups of strata with 'similar' ratios and then applying a ratio estimator to each group of strata gives estimators of total discards that are less biased and more precise.

The collapsed ratio estimator (along with all other ratio estimators) requires an auxiliary variable, both to form ratios and to raise to stratum totals. The natural choice here is the biomass of total demersal fish landings, since we are assuming that the discard ratios of the sampled vessels are typical of those in the fleet. The data reveal no evidence of a strong quarter effect on the discards/landings ratio, so we collapsed the data from all four quarters into a single group and estimated annual discards by

$$\hat{D} = L\frac{\hat{d}}{\hat{l}}$$

where

$$\hat{d} = \sum_q N_q \frac{d_q}{n_q}, \quad \hat{l} = \sum_q N_q \frac{l_q}{n_q}$$

and, in any given year, d_q is the discarded biomass (kg) of all fish species during the visit in quarter q, l_q the landed biomass (kg) of all demersal fish during the visit in quarter q, n_q the number of trips during the visit in quarter q, N_q the total number of registered fishing trips by Clyde *Nephrops* trawlers in quarter q, L the reported total annual demersal landings (kg) by Clyde *Nephrops* trawlers. Total annual demersal fish landings and the total number of fishing trips per quarter were obtained from SEERAD unpublished records.

It is difficult to obtain an appropriate estimate of the variance of $\hat{D}$ without being able to model the sampling mechanism by which the vessels were selected. However, by making some simplifying assumptions, we can obtain a crude estimate that should at least be of the correct order of magnitude. Specifically, we ignore the stratification by quarter and assume the data were collected by simple random sampling. We then use standard theory for ratio estimators (Thompson, 1992) to obtain (ignoring all finite correction factors)

$$\hat{\mathrm{Var}}(\hat{D}) = \left(\frac{L}{\hat{l}}\right)^2 \sum_q \left(\frac{N_q}{n_q}\right)^2 s^2$$

where

$$s^2 = \frac{1}{Q-1}\sum_q \left(d_q - \frac{\hat{d}}{\hat{l}}\, l_q\right)^2$$

and Q is the number of visits that year.

2.3. Modelling temporal trends, and relationships with quarter and mesh size

We modelled three summary measures of fish bycatch:

– the number of fish species discarded per visit,
– the mean length of fish discarded per visit,
– the bycatch biomass per unit effort ($\mathrm{kg \cdot h^{-1}}$) in each visit (strictly, the biomass of fish discards and demersal fish landings).

Note that the number of fish species and mean length are based only on the discarded component of the bycatch, since comparable information was not available for the landings. Nevertheless, the number of fish species discarded can be effectively considered as the number of species caught, since it is unusual to land a species without discarding part of its catch. The loss of information is greater in the case of mean length where, for example, any relationship with mesh size could be confounded with changes in discarding behaviour, and this must be kept in mind when interpreting the results.

The linear model response = year + mesh size + quarter + year × quarter + mesh size × quarter + error was used to analyse the three summary measures of fish bycatch. Mesh size and year were treated as continuous explanatory variables; quarter was treated as a categorical explanatory variable; and the interaction terms year × quarter and mesh size × quarter were included to allow for different relationships with year and mesh size in each quarter. The model was fitted to each response in turn using 'MM regression' (Yohai et al., 1991), a robust regression technique in which the fit is minimally influenced by outliers in either the response variable, the explanatory variables, or both, as implemented in the S-Plus statistical package. Non-significant terms were then removed in a backwards stepwise procedure using robust Wald tests at the 5 % significance level.

The model was modified, however, to account for the different effect of fishing effort (number of hours fishing) on each response. The number of species discarded should increase non-linearly with effort, tending to an upper limit equal to the maximum number of species available to the fishery. To mimic this behaviour, we included log effort as an additional explanatory variable. Mean length should be estimated more precisely as effort increases, so we weighted each mean length observation by the corresponding fishing effort. Finally, the bycatch biomass should tend to increase linearly with effort, which is naturally incorporated by considering bycatch biomass per unit effort. Bycatch biomass per unit effort was also log-transformed to homogenise variances.

A further complication was that seven of the sixty visits were on twin-rig trawls (mostly in the early 1990s). Twin-rig trawls must use mesh size of 80 mm or more, so there is potential confounding between trawl-type and mesh size. To avoid this problem, we restricted the analysis to the 53 visits on single-rig trawls.

Finally, mean length and biomass varied between different species in the bycatch, so we repeated the modelling of mean length and bycatch biomass per unit effort for the five species discarded most often throughout the study period. The only modification was to add 0.1 kg to each biomass measurement, to avoid problems with visits in which no fish of a particular species were caught.

3. RESULTS

3.1. Description of fish discards

During the sixty visits to the fishery up to the autumn of 1998 (106 fishing trips), a total of 36 tonnes of fish were discarded, belonging to 61 fish species from 28 families. *Table II* gives a detailed breakdown of the information collected per visit. On average, each visit consisted of two trips of two to three hauls each. Trips became longer but fewer over the study period, but an average of about 20 h fishing per visit was maintained throughout. Hauls were generally long (around 4 h) and the cod-end mesh size was usually between 70 and 75 mm. Fish landings per visit rarely exceeded 1 tonne, in most cases being below 0.5 tonnes. On average, about 60 % by weight of the fish bycatch was discarded. Around twenty species were usually discarded per visit.

Summary information for the species discarded in more than a quarter of the sampled hauls is given in *table III*. Whiting dominated the fish discarded in the Clyde *Nephrops* fishery. It was discarded in all sampled hauls, and comprised almost 40 % of the discarded fish biomass. Poor cod (*Trisopterus minutus*), long rough dab (*Hippoglossoides platessoides*), hake (*Merluccius merluccius*) and Norway pout (*Trisopterus esmarkii*) were discarded in at least 80 % of hauls. Collectively, these five species determined the overall length frequency of discards. Among them, only whiting and hake have commercial importance, with both species mostly discarded at lengths well below their minimum landing size (27 cm for whiting, 30 cm for hake). In general, the biomass discarded per unit effort was greatest for the most frequently dis

Table II. Summary of the information collected per visit by the Scottish discard sampling programme in the Clyde *Nephrops* trawl fishery between 1982 and 1998.

	Range	Interquartile range	Median	Mean
Trips	1–3	1–2	2	1.8
Hauls	2–16	4–6	5	5.4
Effort (h)	7.8–55.8	16.9–24.3	19.2	20.6
Mesh size (mm)	65–85	70–75	70	73.2
Fish landings (kg)	44–2 250	123–536	224	381
Fish discards (kg)	41–2 838	261–754	396	601
Discarded bycatch (%)	7–93	51–74	63	62
Mean discarded length (cm)	14.5–24.4	18.1–20.3	19.1	19.1
Species discarded	8–29	17–23	21	20

carded species, with the exception of saithe (*Pollachius virens*) and herring (*Clupea harengus*) that were sporadically caught (mainly in the 1980s) and discarded in large amounts. Species discarded in less than a quarter of the sampled hauls ranged from valuable commercial species, such as anglerfish (*Lophius* sp.), mackerel (*Scomber scombrus*), and flounder (*Platichthys flesus*), to small-bodied non-commercial species, such as spotted dragonet (*Callionymus maculatus*), greater weever (*Trachinus draco*), and red bandfish (*Cepola rubescens*).

Figure 2 shows quarterly length distributions of discards for whiting, hake, Norway pout, poor cod, and long rough dab, for visits in the 1980s (1982–1990) and the 1990s (1991–1998). The length distributions were estimated by taking, for each length class in turn, a trimmed mean of the numbers discarded on each visit. There is a clear seasonal evolution in the length distribution of discarded whiting. Whiting recruits enter the fishery in the third quarter, leading to a bimodal length distribution of discards in the second half of the year. By the start of the following year, the upper mode disappears as whiting reach marketable sizes (above 27 cm). There is also some suggestion of a recruitment pulse for hake and poor cod in the fourth quarter. *Figure 2* also shows that the quantities of discarded hake and Norway pout have declined markedly over the study period. Finally, poor cod and long rough dab are caught (and discarded) in much larger quantities in the second half of the year, when they comprise more than one quarter of the total number of fish discarded.

Table III. Species discarded in more than 80 of the 321 sampled hauls in the Clyde *Nephrops* fishery between 1982 and 1998: species name (scientific and common), length distribution (range and mean), mean biomass discarded per unit effort ($kg \cdot h^{-1}$) and frequency of occurrence (% hauls present).

Scientific name	Common name	Length range (cm)	Mean length (cm)	Mean biomass discarded per unit effort ($kg \cdot h^{-1}$)	% hauls present
Merlangius merlangus	Whiting	7–31	19.1	11.73	100
Trisopterus minutus	Poor cod	8–29	15.1	1.61	92
Hippoglossoides platessoides	Long rough dab	5–28	13.9	1.02	91
Merluccius merluccius	Hake	7–37	19.3	2.16	87
Trisopterus esmarkii	Norway pout	8–27	17.0	3.16	80
Glyptocephalus cynoglossus	Witch	5–30	20.0	0.50	79
Pleuronectes platessa	Plaice	10–30	19.3	1.27	75
Limanda limanda	Common dab	6–27	17.5	0.75	67
Gadus morhua	Cod	8–34	22.4	0.90	65
Callionymus lyra	Dragonet	7–30	18.4	0.02	54
Clupea harengus	Herring	11–33	22.1	1.45	52
Melanogrammus aeglefinus	Haddock	9–32	18.1	0.92	49
Pollachius virens	Saithe	15–49	26.9	2.28	41
Eutrigla gurnardus	Grey gurnard	9–27	16.9	0.15	38
Enchelyopus cimbrius	Four bearded rockling	7–28	15.7	0.03	35
Argentina sphyraena	Lesser argentine	8–23	17.6	0.07	32
Lumpenus lumpreateformis	Snake blenny	10–31	22.1	0.02	27
Scyliorhinus canicula	Lesser spotted dogfish	16–77	54.0	0.20	26
Microstomus kitt	Lemon sole	14–27	18.4	0.05	25

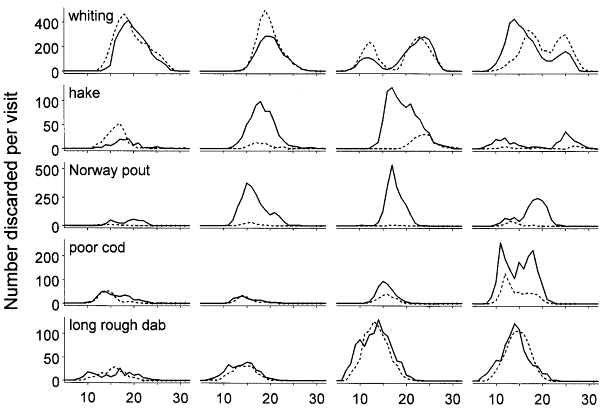

Figure 2. Quarterly length distributions (total length, cm) of whiting, hake, Norway pout, poor cod, and long rough dab discards from the Clyde *Nephrops* fishery for the periods 1982–1990 (solid line) and 1991–1998 (broken line). The quarters run from January–March (left) to October–December (right). The length distributions were estimated by taking, for each length class in turn, a trimmed mean of the numbers discarded on each visit.

3.2. Estimates of total fish discards

Table IV gives:

– reported total annual demersal and *Nephrops* landings by Clyde *Nephrops* trawlers for 1982–1998 (SEERAD unpublished records),

– estimates of total annual fish discards for 1982–1998, with approximate standard errors,

– estimates of total annual *Nephrops* discards for 1991–1998 obtained from the separate *Nephrops* discard programme (I. Tuck, FRS Marine Laboratory Aberdeen, pers. comm.).

The estimates of total annual fish discards range between 318 and 3 027 tonnes, with a mean of 1 761 tonnes. There is large inter-annual variation, possibly related to variation in recruitment, but no evidence of any systematic change over time (robust regression of log total discards against year; $P = 0.73$). The precision of the estimates is generally satisfactory (mean coefficient of variation 38 %) given the low sampling rate. Fish landings have declined over the study period (robust regression of log fish landings against year; $P < 0.0001$), which corresponds to an increase in the average discard rate from about 55 % (by weight) in the 1980s to 70 % in the 1990s.

Averaged over the study period, the biomass of *Nephrops* landings and fish bycatch have been broadly similar, although recently *Nephrops* landings have increased both in absolute and relative terms, possibly due to some strong year classes entering the fishery (I. Tuck, pers. comm.). For the period that *Nephrops* discard estimates are available, the discard ratio for *Nephrops* was low, never exceeding 17 % of the *Nephrops* catch.

3.3. Temporal trends, quarter effects, and relationships with mesh size

The number of species discarded was not related to any of the explanatory variables at the 5 % significance level.

The mean length of discarded fish was positively related to mesh size ($P = 0.004$), but there was no evidence of any temporal trend or any relationship with quarter. The fitted relationship is shown in *fig*

Table IV. Annual estimates (tonnes) of total fish discards (with standard error, SE) in the Clyde *Nephrops* fishery for 1982–1998. No standard error could be calculated for 1982 because there was only one visit to the fishery that year. Also given are the number of visits to the fishery, the number of sampled trips, the total number of registered fishing trips by Clyde *Nephrops* trawlers, the reported total demersal and *Nephrops* landings by Clyde *Nephrops* trawlers (tonnes), and estimates of total *Nephrops* discards (tonnes). The latter are available only for 1991–1998.

Year	Visits		Trips		Fish			*Nephrops*
		Sampled	Fleet	Landings	Discards	SE	Landings	Discards
1982	1	2	10 344	880	1 037		1 798	
1983	4	10	13 808	1 564	1 886	504	3 257	
1984	4	5	12 809	1 332	608	536	2 434	
1985	4	10	15 399	1 583	2 509	797	3 257	
1986	3	6	17 121	1 044	318	151	3 035	
1987	4	8	15 616	853	2 687	540	2 311	
1988	4	8	16 396	1 197	3 027	1 112	3 385	
1989	4	8	16 155	1 214	1 242	279	2 393	
1990	2	4	15 857	1 022	2 411	438	2 435	
1991	4	6	15 711	1 105	2 282	729	2 490	221
1992	4	7	15 016	904	2 479	773	2 126	86
1993	4	8	16 665	888	1 219	510	2 632	243
1994	4	5	11 793	666	1 415	658	1 998	318
1995	4	7	12 812	598	1 607	992	3 501	569
1996	4	6	13 831	587	1 867	850	3 530	564
1997	3	3	12 364	421	1 457	675	3 020	499
1998	3	3	14 314	554	1 886	165	4 107	845

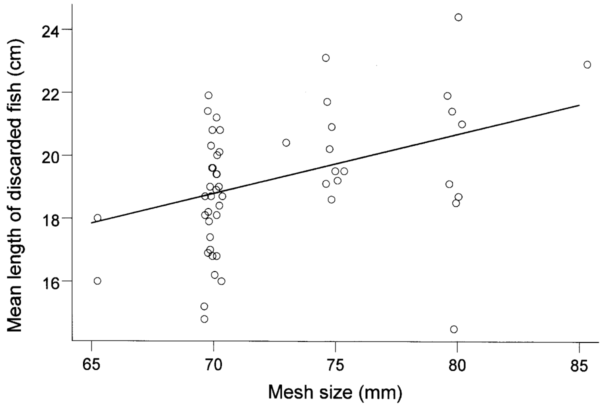

Figure 3. The mean length of fish (total length, cm) discarded on each visit plotted against mesh size (mm). Mesh size has been jittered slightly to avoid overlay. The straight line is the fitted relationship: mean length = 5.61 (4.49) + 0.188 (0.062) mesh size, where the numbers in brackets are the standard errors on the parameter estimates.

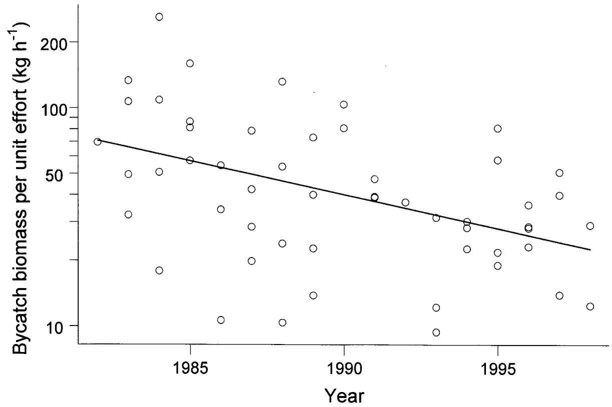

Figure 4. The bycatch biomass per unit effort (kg·h^{-1}) on each visit plotted on a log-scale against year. The straight line is the fitted relationship: log bycatch biomass per unit effort = 145.88 (46.81) – 0.071 (0.023) year, where the numbers in brackets are the standard errors on the parameter estimates.

ure 3. Repeating the analysis by species showed that the relationship with mesh size was driven by a comparable relationship for whiting, long rough dab and Norway pout (P = 0.01, 0.06, 0.10 respectively). In addition, the mean length of discarded whiting decreased over time in the third quarter, but increased over time in the fourth quarter (P = 0.002, 0.001 respectively), suggesting that whiting are recruiting earlier to the fishery (c.f. *figure 2*). Further, the mean length of discarded Norway pout decreased over time in the first and fourth quarters (P = 0.0001, 0.0005 respectively), and the mean length of discarded hake was greater in the second half of the year throughout the study period (P = 0.0003).

The log bycatch biomass per unit effort decreased over time (P = 0.004), but there was no evidence of any relationship with quarter or mesh size. The fitted temporal trend is shown in *figure 4* and equates to a reduction of 68 % in bycatch per unit effort over the study period (95 % confidence interval 32–85 %). Repeating the analysis by species revealed a decline in bycatch biomass per unit effort for hake, Norway pout, and poor cod (P = 0.03, < 0.0001, 0.03 respectively). In addition, the bycatch biomass per unit effort was greatest for poor cod in the fourth quarter of the year (P = 0.004), and for long rough dab in the second half of the year (P = 0.007) (*figure 2*).

Splitting the data into landings and discards separately showed significant declines in the biomass of both fish landings and discards per unit effort (P < 0.0001, P = 0.03 respectively), with estimated reductions of 87 and 56 % over the study period respectively. Of the five species considered in detail, only hake and whiting were both landed and discarded. Hake landings per unit effort were stable over the study period, but hake discards per unit effort declined (P = 0.02). Conversely, whiting discards per unit effort were stable, but whiting landings per unit effort declined (P = 0.02). Note that discards dominated the whiting bycatch (75 % by weight on average), so the significant decline in whiting landings had only a small (and statistically insignificant) effect on the total whiting bycatch.

4. DISCUSSION

Fish discards in the Clyde consist of small fish, mainly young whiting. This is similar to the discards from *Nephrops* trawlers in the Irish Sea (Briggs, 1985) and the North Sea (Evans et al., 1994). The species composition of the fish discards is also similar in the three fisheries, with seven of the ten most discarded species in the Clyde being discarded in large quantities in the Irish Sea, and six in the North Sea. The biggest difference concerns hake, which was caught and discarded in most visits to the Clyde. However, hake was only caught in small amounts in the North Sea, whilst in the Irish Sea it was mainly landed rather than discarded. Haddock and lesser-spotted dogfish (*Scyliorhinus canicula*) were not abundant in the discard samples from the Clyde *Nephrops* fishery, although both species are discarded in large quantities in the west of Scotland demersal fisheries (Stratoudakis, 1997).

On average, an estimated 1 761 tonnes of fish were discarded annually by *Nephrops* trawlers in the Clyde over the study period. In recent years, discards comprised about 70 % by weight of the fish bycatch. However, if anything, these estimates are likely to be too small. Some misreporting in the fishery is known to exist, and correcting for this would increase both the estimates of annual discards and landings (although the estimated discard rate would stay the same because the discards and landings of the sampled vessels are known). Further, to accommodate an observer, the sampled vessels tend to be larger than the fleet average, with arguably the capacity to land a greater proportion of the bycatch. Alternative estimates of total fish discards can be obtained by using the number of trips as the auxiliary variable in the collapsed ratio estimator, rather than total demersal landings. These estimates use only the quantities of fish discarded on each visit, rather than the observed discard rates, and suggest that on average about 4 500 tonnes of fish were discarded annually, with discards comprising about 85 % by weight of the fish bycatch in recent years. The two sets of estimates can be thought of as providing plausible bounds on the quantities discarded, taking into account model uncertainty.

In the few cases where total fish discards have been estimated in small, localised trawl fisheries for crustaceans in the north-east Atlantic, estimates have been of the same order of magnitude as those reported here. Briggs (1985) estimated around 5 000 tonnes of demersal fish were discarded annually by *Nephrops* trawlers in the Irish Sea during the early 1980s. The reported *Nephrops* landings in this fishery were 4 488 t in 1982, indicating a ratio of fish discards to *Nephrops* landings similar to the Clyde. Walter and Becker (1997) reported fish discards of around 4 000 t from the brown shrimp (*Crangon crangon*) trawl fishery in the Wadden Sea, although the only information they provide on the size of the fishery is that it involves 118 beam trawlers from Lower Saxony. However, unlike the Clyde, the estimated total discards of the target species were similar to (2 500 t *Nephrops* in the Irish Sea) or much higher than (27 500 t brown shrimp in the Wadden Sea) the estimated fish discards.

The bycatch biomass per unit effort decreased over the study period, as did both its constituent components, landings and discards biomass per unit effort. However, the decline in landings per unit effort was greater than that in discards per unit effort, corresponding to an increase in the discard rate over time. These results are consistent with the decline in the annual reported total demersal landings and the stable estimates of total annual fish discards (*table IV*), given that the average duration of the sampled trips increased over the study period. Of the five main discarded species, the discarded quantities of whiting and long rough dab remained stable, but there were moderate reductions in the discarded biomass of hake and poor cod, and large reductions in the discarded biomass of Norway pout. The difference is extremely marked for Norway pout, which was almost as dominant as whiting in the 1980s, but has been practically absent from catches in the 1990s.

There was a clear relationship between mesh size and the mean length of discarded fish, with larger mesh sizes associated with larger discarded fish. Although the relationship between mesh size and the number of discarded species was not significant, when mesh size was included in the model, the regression coefficient was negative (coefficient = –0.38, standard error = 0.22) which is consistent with the expectation that higher mesh sizes should be associated with fewer species. Indeed, when the model was fitted by ordinary least squares (more efficient than robust MM regression) the relationship became significant at the 1 % level. These results are intuitively appealing, being compatible with the knowledge on the selection properties of fishing nets; larger mesh openings should allow more small fish to escape, reducing the species richness whilst increasing its mean length. Perhaps surprisingly, there was no evidence of any relationship between mesh size and the biomass of the bycatch.

Our analysis considered only the relationship between mesh size and bycatch. Gear selection properties are also affected by cod-end diameter, extension length, twine thickness and the placement of square mesh panels (Briggs, 1992; Reeves et al., 1992; Armstrong et al., 1998), but this information was not available for the trips observed under the Scottish discard sampling programme. We were also not able to consider the effect of changes in mesh size on the *Nephrops* catch. As Briggs et al. (1999) have recently shown, increasing the mesh size of *Nephrops* trawlers from 70 to 80 mm reduces the catch of *Nephrops* by 20–34 % depending on the twine thickness used. Based on these findings, Briggs et al. (1999) suggested that traditional small *Nephrops* trawlers using a single-rig trawl with 70-mm mesh would suffer serious economic consequences following any increase in the minimum mesh size.

Acknowledgements. We thank the Scottish fishermen who have permitted and facilitated discard sampling, and the staff of the FRS Marine Laboratory, Aberdeen that have contributed to the collection and storage of this information. Ian Tuck kindly provided the annual estimates of *Nephrops* discards in the Clyde and, together with John Hislop and Nick Bailey, made many helpful comments on the text. YS also wishes to acknowledge the European Union for providing financial support for most part of his study on Scottish fisheries discards (Contract Nos. AIR GT93/2696 and FAIR GT95/6010). Finally, we thank the two anonymous referees for their focused comments that greatly helped to improve the original manuscript.

References

Anon., 1980. Council regulation (EEC) No 2527/80 of 30 September1980 laying down technical measures for the conservation of fishery resources. Official Journal of the European Communities L 258/23.

Armstrong, M.J., Briggs, R.P., Rihan, D., 1998. A study of optimum positioning of square-mesh escape panels in Irish Sea *Nephrops* trawls. Fish. Res. 34, 179–189.

Bailey, N., Howard, F.G., Chapman, C.J., 1986. Clyde Nephrops: biology and fisheries. Proc. R. Soc. Edinb. 90, 501–518.

Briggs, R.P., 1985. Catch composition in the Northern Ireland *Nephrops* fishery. Fish. Res. 3, 47–60.

Briggs, R.P., 1992. An assessment of nets with a square mesh panel as a whiting conservation tool in the Irish Sea *Nephrops* fishery. Fish. Res. 13, 133–152.

Briggs, R.P., Armstrong, M.J., Rihan, D., 1999. The consequences of an increase in mesh size in the Irish Sea *Nephrops* fishery: an experimental approach. Fish. Res. 40, 43–53.

Coull, K.A., Jermyn, A.S., Newton, A.W., Henderson, G.I., Hall, W.B., 1989. Length/weight relationships for 88 species of fish encountered in the North East Atlantic. Scot. Fish. Res. Rep. 43.

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

Hislop, J.R.G., 1986. The demersal fishery in the Clyde Sea area. Proc. R. Soc. Edinb. 90, 423–437.

Jermyn, A.S., Robb, A.P., 1981. Review of cod, haddock and whiting discarded in the North Sea by Scottish fishing vessels for the period 1975-1980. ICES CM1981/G:47.

Liggins, G.W., Kennelly, S.J., Broadhurst, M.K., 1996. Observer-based survey of by-catch from prawn trawling in Botany Bay and Port Jackson, New South Wales. Mar. Freshw. Res. 47, 877–888.

Reeves, S.A., Armstrong, D.W., Fryer, R.J., Coull, K.A., 1992. The effects of mesh size, cod-end extension length and cod-end diameter on the selectivity of Scottish trawls and seines. ICES J. Mar. Sci. 49, 279–288.

Stratoudakis, Y., 1997. A study of fish discarded by Scottish demersal fishing vessels, Ph.D. thesis. University of Aberdeen, UK.

Stratoudakis, Y., Fryer, R.J., Cook, R.M., Pierce, G.J., 1999. Fish discarded by Scottish demersal vessels; estimators of total discards and annual estimates for targeted gadoids. ICES J. Mar. Sci. 56, 592–604.

Thompson, S.K., 1992. Sampling. John Wiley & Sons, New York.

Tuck, I.D., Chapman, C.J., Atkinson, R.J.A., 1997. Population biology of the Norway lobster, *Nephrops norvegicus* (L.) in the Firth of Clyde, Scotland – I: Growth and density. ICES J. Mar. Sci. 54, 125–135.

Walter, U., Becker, P.H., 1997. Occurrence and consumption of seabirds scavenging on shrimp trawler discards in the Wadden Sea. ICES J. Mar. Sci. 54, 684–694.

Wieczorek, S.K., Campagnuolo, S., Moore, P.G., Froglia, C., Atkinson, R.J.A., Gramitto, E.M., Bailey, N., 1999. The composition and fate of discards from *Nephrops* trawling in Scottish and Italian waters. EC Study Project Report 96/092.

Yohai, V., Stahel, W.A., Zamar, R.H., 1991. A procedure for robust estimation and inference in linear regression. In: Stahel, W.A., Weisberg, S.W. (Eds.), Directions in Robust Statistics and Diagnostics, Part II. Springer-Verlag, New York.