ICES Journal of Marine Science, 56: 292–298. 1999
Article No. jmsc.1999.0444, available online at http://www.idealibrary.com on IDEAL

# Investigating density-dependent catchability in bottom-trawl surveys

O. R. Godø, S. J. Walsh, and A. Engås

Godø, O. R., Walsh, S. J., and Engås, A. 1999. Investigating density-dependent catchability in bottom-trawl surveys. – ICES Journal of Marine Science, 56: 292–298.

The relationship between density of groundfish in the area swept by a trawl and the catchability was explored. We studied Norwegian and Canadian underwater video observations of cod (*Gadus morhua*), haddock (*Melanogrammus aeglefinis*), and American plaice (*Hippoglossoides platessoides*) in the mouth of bottom-survey trawls and found that there were qualitative differences in escapement and capture behaviour at various densities. Based on these observations, available data from trawl efficiency experiments carried out in both regions were analysed to look for density effects on catchability. For both areas and all species examined, video and trawl efficiency experiments support the hypothesis that the density of fish ahead of the bottom-trawl affects catchability.



Key words: catchability, density, survey, cod, plaice, haddock, trawls.

Received 21 April 1998; accepted 24 February 1999.

*Olav Rune Godø and Arill Engås: Institute of Marine Research, PO Box 1870, N-5025 Bergen Norway. Stephen J. Walsh: Northwest Atlantic Fisheries Center, Dept. Fisheries and Oceans, PO Box 5667, St John's Newfoundland Canada A1C 5X1. Correspondence to O. R. Godø: tel: +47 55 23 8675; fax: +47 55 23 8687; e-mail: olavrun@imr.no*

## Introduction

During annual bottom-trawl surveys, catchability is assumed to be a proportional relationship between catch per unit effort (c.p.u.e.) and stock abundance and constant within and between surveys. Retrospective analysis of catchability coefficients has shown that trends in survey catch-at-age data can develop over time. This has a significant effect on a VPA[1] estimate of stock size when the model is calibrated (tuned) with survey abundance indices (Sinclair *et al.*, 1991; ICES, 1991). When this occurs, it would violate common assumptions made in stock assessment models about the relationship between indices of abundance, catch-at-age, and natural mortality. Recent discussion and simulations in the ICES Arctic Fisheries Working Group on the application of different catchability profiles in tuning the VPA of Northeast Arctic cod have underlined the need for better understanding of variation in catchability (ICES, 1998).

Systematic variation in catchability is a common concern in commercial c.p.u.e. data but is normally assumed to be constant in annual survey data, because the same standard survey gear and sampling methods are used. This implies that the sampling gear always catches the same proportion of all fish accesible to it. However, recent research has shown that systematic variation in catchability to surveys is of concern (Swain *et al.*, 1994; Godø, 1994, 1995; Swain and Kramer, 1995; Smith and Page, 1996).

Fish form schools, layers, or patches in which an individual fish's behaviour is not independent of its neighbours' movements. However, at low densities fish may have the space to act as individuals independently of other fish. Potentially, this may give rise to differences in behavioural reactions of fish in front of the trawl at high and low densities. Such reactions could increase escapement from the trawling zone or increase capture success, both having successive effects on the estimates of catchability and indices of stock abundance.

In this paper, we explore the formulation of a density dependent catchability hypothesis by studying the behavioural dynamics of gadoids and flatfish in front of survey trawls using underwater video recordings. We also examined data from trawl efficiency experiments conducted in the Barents Sea and off the coast of Newfoundland to determine if there is a relationship

[1]VPA is virtual population analysis, a cohort model.

Table 1. Norwegian and Canadian bag trawl experiments showing number of day tows.

| Country | Year | Month | Gear | Species | No. tows |
|---|---|---|---|---|---|
| Canada | 1994 | January | Campelen | Cod | 7 |
| | | | | Plaice | 7 |
| Canada | 1994 | January | Engel | Cod | 7 |
| | | | | Plaice | 7 |
| Norway | 1995 | March | Campelen | Cod | 13 |
| | | | | Haddock | 13 |

between catchability and density to support our hypothesis. The significance of these findings to the reliability of survey trawl indices of abundance will be discussed.

## Materials and methods

### Video experiments

Underwater video observations of fish in the trawl mouth were examined to formulate qualitative descriptions of fish behaviour. Direct observations of cod and haddock behaviour in the mouth of the trawl were carried out off the coast of northern Norway in March 1994. The studies were done in daylight at 70–90 m. A self-recording silicon intensified tube (SIT) video camera was mounted on the centre of the headline of a standard Norwegian bottom-sampling trawl (Engås and Godø, 1989). The camera was orientated to view the centre of the footgear. No artificial light was utilized. Similar video studies of cod and flatfish were carried out off the southern coast of Newfoundland in September 1995 during daylight and at depths of 60–70 m. All trawls were towed at a standard speed of 3 knots.

The videotapes were later reviewed, independently, and the behaviour of fish was classified according to various fish densities in the trawl mouth. Attempts to quantify these observations were unsuccessful. Cod and haddock were the dominant species in the Norwegian experiments. In the Canadian experiments, American plaice and cod were the two main species.

### Trawl efficiency experiments

Trawl efficiency can be measured by attaching bag trawls underneath the trawl to capture downward escaping fish passing underneath the footgear (Engås and Godø, 1989; Walsh, 1992; Godø and Walsh, 1992; Dahm and Weinbeck, 1992). We examined previously unreported survey trawl efficiency data from Norwegian and Canadian experiments, which measured escapement of fish underneath the survey trawl, to explore the relationship between fish density and survey catchability.

The Norwegian trawl data were collected off the northern Norway coast in 1995 at water depths of about 250 m (Table 1) using the standard survey trawl: Campelen 1800 shrimp trawl. This three bridle shrimp trawl was rigged with 40 m sweeps, 35.6 cm diameter rockhopper footgear, and a 20 mm mesh size codend. For the purpose of catching downward escaping fish, three bag trawls were mounted under the trawl in the manner described by Engås and Godø (1989). Tow duration was, in most cases, 20 min at a towing speed of approximately 3 knots.

The Canadian data were collected off the east coast of Newfoundland in 1994 at water depths ranging from 70 to 416 m (Table 1) using two bottom trawls: (1) the old standard survey trawl, the Engel 145 High Lift otter trawl[2] rigged with three bridles and 54 m sweeps, 35.6 cm rockhopper footgear, and a 29 mm codend liner; and (2) the new standard survey trawl, the Campelen 1800 shrimp trawl rigged with 40 m sweeps, 35.6 cm diameter rockhopper footgear, and a 12 mm mesh liner in the codend (see McCallum and Walsh 1996 for rigging details of both gears). Similar to the Norwegian experiment, three bag trawls were mounted underneath the main trawl covering 100% of the fishing area of the main trawl as illustrated in Walsh (1992). A standard tow duration of 15 min and a standard survey towing speed of 3.0 knots were used.

### Analysis of the trawl data

The density of fish in the trawl mouth was approximated by summing the catch data from the main codend and bag trawl codends. Trawl efficiency (EFF) was calculated as the ratio of the catch in the main trawl (mt) to sum of catches from the main trawl and bag trawl (bt) catches, i.e. EFF=mt/(mt+bt). The hypothesis of density dependency effects on trawl efficiency was explored through graphical presentations and least square regressions. For the regression analysis, an arcsine transformation suitable for proportional data was used to normalize the data. As cod reacted similarly to the trawls used in both the Norwegian and Canadian experiments, the data was combined. Haddock and plaice data were treated separately.

[2]During regular surveys this trawl was rigged with bobbin footgear.

Table 2. The size groups and catch frequences in the Norwegian and Canadian trawl efficiency experiments.

| Size | Cod and haddock (cm) | Cod Norway (%) | Haddock Norway (%) | Cod Canada (%) | Plaice (cm) | Plaice Canada (%) |
|---|---|---|---|---|---|---|
| Small | 0–29 | 58 | 53 | 18 | 0–19 | 43 |
| Medium | 30–49 | 32 | 42 | 82 | 20–29 | 25 |
| Large | 50+ | 10 | 4 | 0 | 30+ | 32 |

As trawl efficiency of cod, haddock, and plaice is strongly size dependent (Engås and Godø, 1989; Walsh, 1992), we used the videos to develop a relative size classification scheme: small, medium, and large fish (see Table 2). This scheme was based on comparing the size of the fish to the size of the rubber disks in the footgear. Precise size determination of the fish from videos was impossible due to the unknown position of the individuals in the observation field of the camera. Behaviour studies of small fish in front of trawls using underwater videos are difficult because they have little swimming endurance and readily escape capture (independent of density) by remaining close to the bottom below the net (Walsh, 1991). Therefore, small fish were excluded from the analyses. Because some species school by size, which may vary from haul to haul, the analysis was based on densities of two size categories: medium and large size fish. Length frequency data of fish in these two size categories were then divided into 5 cm intervals and the efficiency was calculated for these length classes. Only daytime video observations of fish behaviour and catch data were used in this analysis.

# Results

## Video observations of fish behaviour

Based upon examination of several daylight underwater video recordings of fish we offer a qualitative description of the behaviour of medium and large size gadoids and plaice in the mouth of the trawl. These behaviour observations have also been evident in many video observations from other Canadian and Norwegian monitoring events (see Engås, 1994). They are described as follows:

### *Cod and haddock*

Cod and haddock were observed reacting to the trawl footgear in a similar manner. As it was often difficult to discriminate one species from the other in the videos, we combined the observations of their swimming behaviour in front of the footgear together.

*Low densities.* When one or two medium to large size cod or haddock arrived in the trawl mouth they were observed swimming close in front of the footgear, exhibiting a characteristic kick and glide swimming behaviour while criss-crossing the trawl mouth (Figure 1a). These fish, which we call loners, were observed swimming very close to the seabed. Their turn-over rate[3] was high. During the criss-crossing movements some fish turned towards gaps in or beneath the footgear rigging and escaped. Other fish were observed turning into the net and being caught.

*High densities.* When five or more fish of similar size were observed entering the trawl mouth area together, a school type structure was formed in which the fish exhibited uniformed behaviour. These fish, which we call schoolers, swam approximately 0.5–1 m off the bottom and were orientated to the towing direction. Although the schoolers were observed keeping well ahead of the footgear (Figure 1b), they exhibited very little frightened behaviour. Generally, when one fish turned to enter the trawl several others would follow. Their turnover rates were lower in comparison with the loners.

On some occasions, loners and schoolers were observed in the video recordings together. In this case, the loners did not swim forward to join the schooling group (Figure 1b) and both groups appear to act independently in the manner described above. However, the characteristic criss-crossing behaviour of the loners was often interrupted in this situation. The turnover rates were variable.

### *American plaice*

Flatfish such as American plaice,[4] are non-schoolers and are not very powerful swimmers (Main and Sangster, 1981; Winger *et al.*, 1999). Observations showed that after repeated encounters with the footgear, plaice generally exhibited one of the following three behaviours:

[3] The rate at which fish upon entering the trawl mouth area will either be caught by the net or escape.

[4] The group of flatfish that we refer to here are the more common bottom flounders such as American plaice and North Sea plaice (*Pleuronectes platessa*), etc. It doesn't include the more powerful swimming halibuts which are capable of swimming in front of the trawl for longer periods. For brevity, we have shorten the name to plaice.

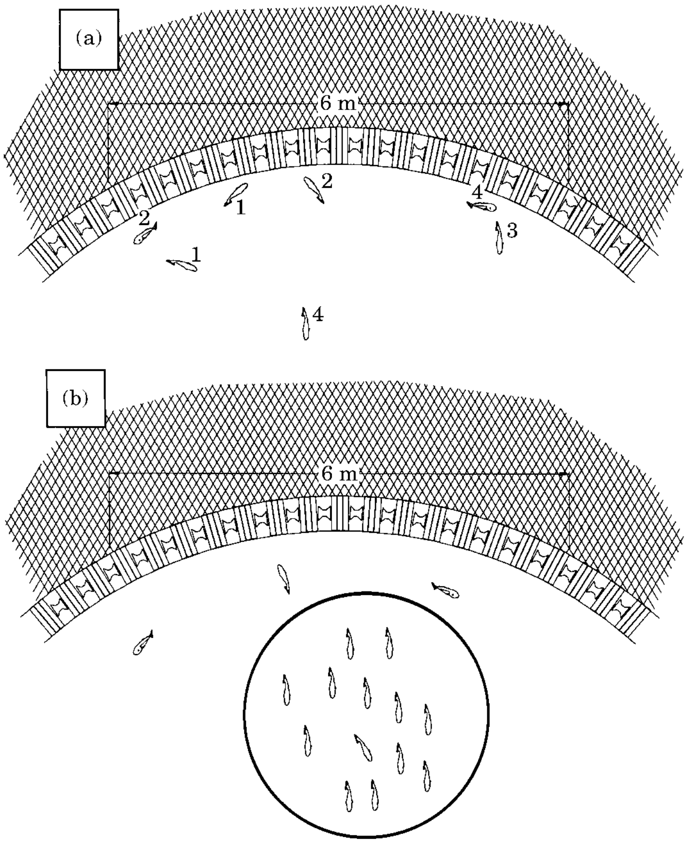


Figure 1. Schematic presentation of distribution and behaviour of gadoids in front of the ground gear of loners (a) from different observation events (1–4), and loners-schoolers (b, schoolers are encircled) from one event.

(1) they burst upward and flip backward into the net; (2) they rise off bottom and allow the footgear/net panel to pass under them and then turn and swim into the net; or (3) they slow down or stop swimming whereby the footgear passes over the top of them and they escape the trawl zone (see also Main and Sangster, 1981).

*Low densities.* When individual medium and large size plaice were observed in the trawl mouth they swam close to bottom and slightly ahead of the footgear. As the footgear came closer, the fish were observed to either swim ahead for a short distance in a zigzag pattern or swim in a lateral direction across the footgear, especially those newly disturbed from the bottom. During these movements, some plaice were observed turning and passing through spaces between or underneath the footgear. Other plaice either swam upward from the bottom and into the net or swam slower than the speed of the approaching footgear and passed underneath the trawl. Similar to gadoids at low densities, the turnover rate was high.

*High densities.* As the density of plaice increased in the trawl mouth, the zigzag behaviour pattern was often observed to be disrupted. Some plaice observed swimming in the centre of the trawl mouth often encountered other plaice swimming towards them. When that happened, one or more of the plaice swam rapidly upward and into the net. Other plaice were observed to swim upward from the bottom and then swim in a forward direction and were eventually caught. The turnover rate was low at high densities.

### *Trawl efficiency experiments*

The size groups and catch frequencies from the trawl efficiency experiments using bags mounted underneath the trawl to estimate escapement are represented in Table 2. Trawl catches from the Norwegian studies showed that cod and haddock were in the size range of 20–80 cm with mean lengths of 39.6 and 49.1 cm, respectively. In the Canadian experiments, cod ranged in length from 5 to 97 cm with a mean length of 37.9 cm and plaice ranged in length from 6 to 67 cm with a mean length of 24.1 cm.

The catchability coefficients for all species and size groups were variable although there was a tendency to observe low catchability at low densities and high catchability at high densities (Figure 2). The slope of the least

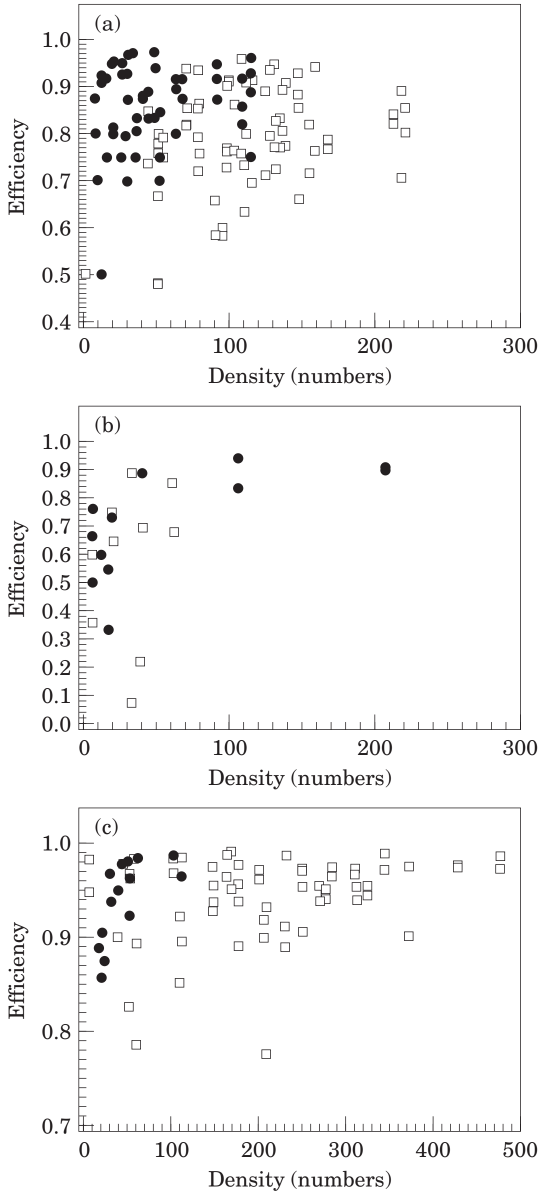


Figure 2. Density-dependent trawl efficiency of cod (a), plaice (b), and haddock (c) during daytime observations. Raw data are used in these plots with squares representing medium size fish and dots representing large fish. Density refers to the number of fish caught at each trawl station for each size category.

square regressions was significantly different from zero in four out of six cases (Table 3). We interpreted the graphical and statistical analysis as supporting evidence of a relationship between density and catchability.

## Discussion

The underwater video observations illustrate the differences in the reaction of fish in front of the trawl mouth

Table 3. Parameter estimates from the least squares regression of trawl efficiency against density (y=ax+b). Data was normalized using an arcsine transformation. The p value gives the probability of slope equal to zero.

| | Regression parameters | | | |
|---|---|---|---|---|
| | a | b | $R^2$ | p |
| Cod medium | 0.0011 | 0.81 | 0.08 | 0.02 |
| large | 0.0008 | 1.02 | 0.02 | 0.29 |
| Haddock medium | 0.0003 | 1.20 | 0.10 | 0.05 |
| large | 0.0029 | 1.11 | 0.44 | 0.01 |
| Plaice medium | 0.0045 | 0.50 | 0.07 | 0.46 |
| large | 0.0027 | 0.67 | 0.51 | 0.01 |

at low and high densities. We are confident that they are objective because they were formulated independently in two different regions and based on different videos. These observations of cod, haddock, and plaice behaviour indicate that density-dependent changes in swimming behaviour occur in the mouth of the trawl. We interpret the analysis of video observations and trawl efficiency data as support for the validity of our hypothesis.

We recognize several limitations in this present approach for investigating a density effect on catchability and at least three should be mentioned. Firstly, we are restricted to investigating the effect of fish density on escape rates in the trawl opening, i.e. the area covered by the trawl bags (area between wings and footgear) and cannot comment on what is happening in the area beyond the wings and the trawl doors. Our primary interest in using the trawl efficiency data was to explore the validity of the hypothesis, i.e. not test it, that the catchability of groundfish is systematically affected by density of fish ahead of the trawl. Secondly, using catch as the applied density measure may not necessarily be the best one. In theory, the same catch could be obtained from a standard fishing haul when the study area is occupied by evenly distributed individuals at a low density compared to when encountering the only patch of fish in the area containing the same number of individuals. The spatial structure of fish aggregations at each sampling station prior to arrival of the survey vessel, i.e. under undisturbed conditions, was unknown. Video observations of the trawl mouth in experimental studies, like those presented here, indicate that fish normally arrive in the bosom area of the footgear at varying rates which we suspect is related to the spatial structure of fish densities in the trawl path ahead of the trawl doors. Thirdly, several of the trawl efficiency experiments in both regions were carried out in depths greater than the depth of the video observations. Light levels are expected to decrease with depth, however, empirical studies of this depth effect on catchability have not been conducted.

We have no direct method of testing this assumption with our database.

Density-dependent catchability has been used to explain unexpected results from other trawl efficiency experiments and "year effects" in catchability analyses of survey data. Engås and Godø (1989) observed that in comparative trawling experiments with long and short sweeps, the catch rates of large cod and haddock increased substantially with increasing sweep length more than could be explained by the expansion of the area swept by the trawl doors. Such an increase in density within the mouth of the trawl would increase catchability (see also Dickson, 1993a,b). Annual trawl surveys are expected to give precise information on abundance and composition of stocks under an assumption of constant catchability. However, catchability can be highly variable depending on spatial structure of the stock in the survey area at the time of the survey (Swain *et al*., 1994; Swain and Kramer, 1995; Smith and Page, 1996). For example, Godø (1994, 1995) showed that bottom-trawl abundance indices of the Barents Sea cod tended to be biased downward compared to VPA indices, when the stock was low and biased upward at higher abundance. If our hypothesis is valid, then a catchability differentiation on the individual haul level due to differences in fish density in the trawl mouth would explain how reduced catchability at low densities, when compared to high densities, occurs.

When the spatial structure of a given population is constant from year-to-year then a density–dependent relationship is not a problem. However, if the spatial structure changes then systematic variation in catchability may occur and the reliability of the survey time series could be in doubt. For example, between 1983 and 1991, the average catch per tow (c.p.u.e.) of northern cod (Northwest Atlantic Fisheries Organisation Management Divisions 2J3KL) off the northeast coast of Newfoundland ranged between 80 and 205 fish per tow. However, from 1993 to 1997 the c.p.u.e. has dropped to around two cod per tow (D. Stansbury, Dept. Fisheries and Oceans, St John's, Newfoundland, pers. comm.). In this critical situation, the spatial structure of the stock has changed considerably and, if our hypothesis is correct, then the ability to understand and evaluate this stock development based upon annual surveys is potentially low.

## Conclusions

Although there are several limitations in the data sets we have used, we believe that we have demonstrated a plausible connection between fish density and survey trawl catchability. Nevertheless, we recommend that empirical studies, which explore this source of variation in catchability, be conducted to test this hypothesis. Variation in light levels and its effect on catchability at different depths should be included in this research. Improving our understanding of natural and trawl induced trawl behaviour, as sources of variation in survey catchability and stock assessment, can only occur by conducting such studies which directly measure fish behaviour and take into account the spatial structure of fish densities in the entire trawl zone.

## Acknowledgements

This paper benefited from reviews by Ray Bowering and Mark Simpson at Northwest Atlantic Fisheries Center (NAFC) and discussions with Michael Pennington at the Institute of Marine Research as well as the two anonymous reviewers. Special thanks to Barry McCallum at NAFC for assistance in collecting efficiency data.

## References

Dahm, E., and Weinbeck, H. 1992. Escapement of fish underneath the groundrope of a standard bottom trawl used for stock assessment purposes in the North Sea. ICES CM 1992/B:20.

Dickson, W. 1993a. Estimation of capture efficiency of trawl gear. I: Development of a theoretical model. Fisheries Research, 16: 239–253.

Dickson, W. 1993b. Estimation of capture efficiency of trawl gear. II: Testing a theoretical model. Fisheries Research, 16: 255–272.

Engås, E. 1994. The effects of trawl performance and fish behaviour on the catching efficiency of demersal sampling trawls. *In* Marine fish behaviour in capture and abundance estimation, pp. 45–68. Ed. by A. Fernö and S. Olsen. Fishing News Books, Oxford.

Engås, A., and Godø, O. R. 1989. Escape of fish under the Norwegian sampling trawl and its influence on survey results. Journal du Conseil International pour l'Exploration de la Mer, 45: 269–276.

Godø, O. R. 1994. Factors affecting reliability of groundfish abundance estimates from bottom trawl surveys. *In* Marine fish Behaviour in capture and abundance estimation, pp. 166–199. Ed. by A. Fernö and S. Olsen. Fishing News Books, Oxford.

Godø, O. R. 1995. Relationships between survey indices of recruitment and abundance estimates from VPA of Northeast Arctic cod. *In* Precision and relevance of pre-recruit studies for fisheries management related to fish stock assessment in the Barents Sea and adjacent waters, pp. 199–206. Ed. by A. Hylen. Proceedings of the sixth IMR-PINRO Symposium, Bergen, Norway, 14–17 June 1994. Institute of Marine Research, Bergen.

Godø, O. R., and Walsh, S. J. 1992. Escapement of fish during bottom trawl sampling—implications for resource assessment. Fisheries Research, 13: 281–292.

ICES 1991. Report of the Working Group on Methods of Fish Stock Assessment. ICES CM 1991/Assess:25.

ICES 1998. Report of the Arctic Fisheries Working Group, ICES Headquarters 20–28 August 1997. ICES CM 1998/Assess:2.

Main, J., and Sangster, G. I. 1981. A study of the fish capture process in a bottom trawl by direct observations from an underwater vehicle. Scottish Fishery Research Report, 1981: 23 p.

McCallum, B. R., and Walsh, S. J. 1996. Groundfish survey trawls used at the Northwest Atlantic Fisheries Centre, 1971–present. NAFO Scientific Council Studies, 29: 93–104.

Sinclair, A., Gascon, D., Boyle, R., Rivard, D., and Gavaris, S. 1991. Consistency of some Northwest Atlantic groundfish stock assessments. NAFO Scientific Council Studies, 16: 59–77.

Smith, S. J., and Page, F. H. 1996. Associations between Atlantic cod (*Gadus morhua*) in the southern Gulf of St Lawrence. Canadian Journal of Fisheries and Aquatic Sciences, 50: 1255–1264.

Swain, D. P., and Kramer, D. L. 1995. Annual variation in temperature selection by Atlantic cod, *Gadus morhua*, in the southern Gulf of St Lawrence, Canada and its relation to population size. Marine Ecology Progress Series, 116: 11–23.

Swain, D. P., Nielsen, G. A., Sinclair, A. F., and Chouinard, G. A. 1994. Changes in catchability of Atlantic cod (*Gadus morhua*) to an otter-trawl fishery and research survey in the southern Gulf of St Lawrence. ICES Journal of Marine Science, 51: 493–504.

Walsh, S. J. 1991. Diel variation in availability and vulnerability of fish to a survey trawl. Journal of Applied Ichthyology, 7: 147–159.

Walsh, S. J. 1992. Size dependent selection at the footgear of a groundfish survey trawl. North American Journal of Fisheries Management, 12: 625–633.

Winger, P. D., He, P., and Walsh, S. J. 1999. Swimming endurance of American plaice (*Hippoglossoides platessoides*) and its role in fish capture. ICES Journal of Marine Science, 56: 252–265 (this issue).