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Catches of Greenland halibut (*Reinhardtius hippoglossoides*) in deepwater ghost-fishing gillnets on the Norwegian continental slope

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Abstract

Fishing gear may continue to fish after it has been lost. Large catches have been observed during cruises to retrieve lost gillnets in Norwegian waters, especially in the fishery for Greenland halibut (*Reinhardtius hippoglossoides*). The Norwegian Greenland halibut is overexploited, and there is serious concern about the effect of lost nets on this stock. Catches in deliberately lost gillnets were studied in the fishery for Greenland halibut off the coast of mid-Norway in July 2000 and June 2001. Gillnet fleets were deployed at depths of between 537 and 851 m, and the soak time ranged from 1 to 68 days. Most of the catch consisted of the target species, and the proportions of different species did not change with soak time. All individuals caught were categorized in terms of seven condition states. A gradual shift from fresh to decomposed individuals over time was evident. The catching efficiency of gillnets decreased with soak time, presumably due to the weight of the catch causing the headline height to decrease, and after 45 days was only about 20–30% of that of nets used in the commercial fishery. Catch rates were estimated after stabilization at 67–100 and 28–43 kg per day per gillnet fleet in 2000 and 2001, respectively. The results indicated that gillnets lost in this area continue to fish for long periods of time. Annual losses of nets need to be quantified in order to estimate the effects of ghost fishing on stock levels, a figure that is currently lacking. © 2003 Elsevier B.V. All rights reserved.

Keywords: Ghost fishing; Greenland halibut; Catching efficiency; Continental slope; Lost gillnets

1. Introduction

Fishing gear may continue to fish after it has been lost, a process known as 'ghost fishing' (Breen, 1990). Gillnets may be lost for various reasons. Strong currents can force the buoy below the surface, where it will gradually collapse. Misjudging currents during setting can lead to displacement of gillnet fleets from their intended positions. Objects such as rocks

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and corals on the seabed and wave action during bad weather can lead to rupture of the buoy line or gillnets. Gear conflicts can lead to the displacement of fleets or destroyed nets (e.g. by trawlers) and propellers can cause gillnets to be lost by cutting off their end markers.

Research has concentrated on estimates of net loss (e.g. Carr and Cooper, 1987), the use of degradable materials (Carr et al., 1992) and impacts on endangered species such as turtles (Carr, 1987), mammals and birds (Colema and Wehle, 1983; Anon., 1992, 1995). In recent years, catch rates and the evolution

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of lost nets have been studied by following up gillnets deliberately lost in shallow waters (Kaiser et al., 1996; Erzini et al., 1997). The results showed that catches of fish approached zero after a short time as a result of reduced headline height caused by the accumulation of fish and crustaceans, greater net visibility due to catch and bio-fouling, and destruction of the nets by wear and tear. However, concern has been expressed that the effective fishing life-span of nets lost in deeper waters may be longer (Erzini et al., 1997).

The Norwegian Directorate of Fisheries carries out annual retrieval cruises in Norwegian waters (Anon., 1983–1999). Three anchors connected to a beam are towed behind a charted trawler at specific locations identified by fishermen, and at random in areas of high gillnet effort. Between 1983 and 1997, a total of 6759 gillnets were retrieved (unpublished data, Norwegian Directorate of Fisheries), with the most conspicuous catches being found in Greenland halibut (*Reinhardtius hippoglossoides*) nets retrieved from depths of more than 500 m along the continental slope. Estimates of the age of these nets has demonstrated that gillnets lost more than 8 years earlier were still catching fish (author's observation), with the potential for substantial cumulative catches.

The Norwegian Greenland halibut stock is in poor state (Bowering and Nedreaas, 2000) and estimates of this unaccounted ghost-fishing mortality is needed. The characteristics and dynamics of ghost-fishing nets are, however, poorly understood and little studied, in particular at great depths (Carr et al., 1992) owing to the difficulty of making direct observations (Kaiser et al., 1996), for example, by scuba (Carr et al., 1985) or submersibles (Carr and Cooper, 1987). This paper describes a solution to this methodological problem based on setting out gillnets and retrieving them after various soak times, i.e., simulating ghost-fishing nets. This method allows comparisons of catch (e.g. abundance, composition) and gillnet characteristics (e.g. wear and tear, fouling) over time. The experiments were performed in the Greenland halibut fishery off mid-Norway at depths exceeding 500 m.

2. Materials and methods

The experiment was carried out between 17–24 July 2000 and 12–27 June 2001. The experimental

site was located at Storegga ($63^{\circ}30'N$, $05^{\circ}30'$) on the continental slope 70 nm miles off the coast of mid-Norway where there is a commercial gillnet fishery for Greenland halibut (Fig. 1). Gillnets were deployed on plateaux at depths of 537–851 m (Table 1), where water temperatures ranged from -1 to 5 °C and the seabed comprises sand and mud, with harder bottoms of stones and rocks and occasionally corals around the edges.

Commercial gillnetters were chartered for the experiment. Monofilament (0.6 mm) gillnets, 27.5 m in length and 5.1 m high, were combined in fleets of 27–30 nets. Since the fleet lengths varied, all results were standardized to 30 gillnets per fleet. Catch rates are given as kilogram per fleet (kg/825 m net). The headline was 12 mm "Megafloat" with a buoyancy of 40 g/m. In addition, one float ring (Rosendal 200/42, buoyancy 400 g) was attached to the headline of each net, giving a total float of 54.5 g/m net. The 12 mm lead footrope weighed 250 g/m. The mesh size (stretched) was 180 mm, with a hanging ratio of 0.5. The fleets

Table 1	
Experimental	schedule

Apermentar	schedule

Deployed	Retrieved	Soak	Ν	Water
		time	(fleets)	depth
		(days)		(m)
Trial 1 (2000)				
3 June	18 July	45	4	630-652
12 July	19 July	7	2	583-657
12 July	17 July	5	2	639–648
17-20 July	20-23 July	3	7	593-667
17-22 July	19–24 July	2	3	611–639
20 July	22 July	1	3	537–667
Trial 2 (2001)				
6 April	13 June	68	2	668
24 April	12 June	49	2	648–646
24 May	14 June	21	2	611–629
6 June	16 June	10	1	648
6–13 June	14-21 June	8	2	629–648
16 June	22 June	6	3	648
14-16 June	19–21 June	5	5	666–685
12-22 June	16-26 June	4	6	616-685
13-22 June	16-25 June	3	11	646-814
20-25 June	22–27 June	2	8	648-851
21 June	22 June	1	1	648

^a Fleets were deployed in spring in both years, and retrieved during a limited period in July (2000) and June (2001), thereby reducing variation in experienced fish concentrations for comparison of commercial and ghost-fishing catch rates.



Fig. 1. Geographical location of experimental area (shaded) on the continental slope 70 nm off the Norwegian coast.

were set down the slope and were anchored at the deepest end by a 105 kg anchor attached to the surface buoy by a 22 mm buoyant "Danline" at the bottom and midwater, and a 18 mm leadline in the upper surface zone.

Nets losses may be due to several causes and, in simulation studies, it is necessary to single out one. The loss of end markers and the displacement of fleets by strong currents are the main causes of losses of gillnets set on the continental slope. This type of loss probably does not affect the configuration of the net, and traditional setting for our experimental fleets was therefore adopted.

Given the difficulties in making direct quantitative observations at great depths (see above), we had to find a way to study the ghost net catches over time. It was expected that captured fish would gradually start to decompose and that the relative proportion of fish in different decomposition states would be correlated to the soak time. On the basis of knowledge from earlier retrieval cruises and observations during the first hauls, seven decomposition stages were identified:

- 1. *Alive fresh*. The fish is alive and shows no sign of morphological damage, uniformly dark colour and no faded gills noted.
- 2. Alive some damage. The fish is alive; disrupted colouring with brighter patches unevenly distributed over the body. Physical damage such as cuts, scratches and skin lacking between fin rays caused by gillnet twine/thread.
- 3. *Dead fresh*. Faded gills and glossy eyes (contraction/rigor might occur).
- 4. Dead some damage. Similar to stage 2, but dead.
- Dead extensive damage. Damage indicators as above, but this stage is characterized by small holes in the flesh caused by scavengers (amphipods and isopods), otherwise most parts of the body still

intact. Other criteria that also qualified were white skin or some areas of exposed flesh.

- 6. *Dead severely damaged*. Bones partially exposed (protruding from flesh), intestines missing, larger parts of fish might be removed. Body (remains) penetrated by small holes. Both fish clearly partially eaten and those in the process of bacterial decay were included in this stage.
- 7. Bone relics. Only skeleton or parts of it remaining.

All fish observed were classified according to this system, giving us a record of the quality composition at different soak times, and the successive development of the different stages with time.

The quantity (number) of fresh fish (f = stages 1–4) in ghost nets (g) was compared with that taken in commercial nets (c), thereby giving an index of ghost net catching efficiency:

$$Efficiency_{g} = \frac{Catch_{f,g}}{Catch_{f,c}}$$
(1)

A requirement is that the fleets fishing are as close as possible in space and time (but sufficiently far apart to avoid any influence of parallel fleets) in order to equalize natural variation between sets. It was, therefore, attempted to set fleets within a limited geographical area (Fig. 1). Commercial catch rates (kg/fleet/day) were calculated by dividing total (stages 1–7) cumulative maximum catch (number/fleet) by soak time for the two trials, respectively, and convert it to kilogram using mean weights obtained from subsamples of live specimens of the catch. Numbers instead of kilogram were used in the first instance to avoid weight bias from decomposing specimens. This commercial catch rate was then used to calculate ghost-fishing catch rate during the experimental periods as:

$$Catch rate_{g} = Efficiency_{g} \times Catch rate_{c}$$
(2)

The gillnets were repeatedly inspected to ensure similar catching properties in the course of short soak times (damaged gillnets were replaced) and to detect any signs of wear and tear or other changes in appearance that might influence catching efficiency during long soak times. This process included noting torn nets, stones, corals, debris, catching method (gilling, wedging or tangling), the presence of fish lice along the vertical extension, and fouling. In the first trial, the main aim was to find a method for investigating ghost-fishing nets at these depths. In the second trial, the procedures were repeated and soak times extended, and in addition a complete species identification and quantification were carried out, in order to detect any change in catch composition with soak time.

3. Results

Greenland halibut made up about 80% of the total catch in numbers in the second period (trial 2). The species composition did not differ with soak time for the four main species caught: Greenland halibut, roughhead grenadier (Macrourus berglax, 13%), Arctic skate (Raja hyperborea, 4%) and thorny skate (*Raja radiata*, 2%) (χ^2 -test, d.f. = 33, w = 45.11). Hereafter, the term "catch" refers only to catch of Greenland halibut. A total of 6478 and 8092 halibut were caught and classified into one of seven conditions in the first and second trials, respectively. Mean weight in 2000 was 2.69 and 2.98 kg in 2001. The manner of enmeshing was monitored for a subsample of nets and showed that 89% of the fish were caught by the meshes being behind their operculum and in front of their stomach bone (axonost) and the leading edge of the dorsal fins. Virtually all of the gillnets retrieved were in the same condition as when they were set, with no signs of wear and tear.

The frequency distribution of the states of the catches at the different soak times showed a gradual shift from generally fresh (stages 1-4) up to 22 days to decomposed (stages 5-7) after 45 days (Fig. 2). However, a change from the 9th to 10th day (especially stage 4) seemed to be the onset of a transition period that continued to somewhere between 22 and 45 days after which the decomposed stages dominate. The presence of live fish in the nets after long soak times demonstrated that the nets were still catching fish after 68 days in the sea. All seven stages of deterioration were observed after soak times of only 24 h, probably due to the activities of amphipod and isopod scavengers (fish lice). Lice were registered in almost 100% of fish at stages 5 and 6 at short soak times (<5days), 85% at 5, 6 and 8 days and 60% at 68 days (soak times not mentioned were not monitored for lice). The frequency of stages corresponded well between the two trials where direct comparisons could be made (1, 2, 3, 5 and 7 days), especially for stage 1.

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Fig. 2. Distribution of catches in the two trials at different stages of deterioration at different soak times (no index: experiment 1, asterisk (*): experiment 2).



Fig. 3. Total catches per fleet (30 gillnets) at different soak times. Note different y scales and non-linear x scales according to registration days.



Fig. 4. Loss of catching efficiency calculated as reduction in catches at stages 1–4 compared to day of maximum catch for each period and position. 100% is the efficiency observed at commercial soak times. Bars indicate standard deviation.

The accumulative catch rose until day 5 in trial 1 when fish concentrations were high while it took 10 days in trial 2 before a decrease was observed. This reflects the annual variability in fish concentrations. The proportion of decomposing fish rose with soak time, and became greater than the proportion of fresh fish between 7 and 45 days in trial 1 and between 21 and 49 days in trial 2 (Fig. 3). At day 4 much lower total catches were obtained in experiment 2. Although we attempted to place settings close to each other, these fleets were set off position due to lack of space in the core area.

Capture efficiency was calculated (using Eq. (1)) for various soak times, and tended to stabilise between 21 and 45 days at 20–30% of the initial or commercial efficiency (Fig. 4). The commercial catch rates were 123 and 48 kg/fleet/day after 5 and 8 days in Experiments 1 and 2, respectively. By using these figures in Eq. (2), ghost-fishing catch rates of approximately 67–100 kg/fleet/day in experiment 1 and 28–43 kg/fleet/day in experiment 2 were obtained.

4. Discussion

To the best of our knowledge this is the first study to examine catches in simulated lost nets at depths greater than 500 m. One study has been performed at moderate depths (117-135 m) in the Bay of Biscay (Puente et al., 2001), while four studies have been carried out in shallow water (Carr et al., 1992; Erzini et al., 1997; Kaiser et al., 1996; and present issue). In these studies (and in the majority of retrieval cruise reports), the sequence of development observed or assumed is that fish catches fall and generally cease as the weight of the catch and tidal action force the headline down, while further entanglement of scavenging crustaceans and fouling effectively reduce the effective operating life of lost nets. In our study, a rise in catches was observed up to the eighth day, followed by a transition period with decreasing catches and higher proportion of late decomposition stages between 9 and 45 days and thereafter towards stabilised low catches and dominance of decomposed stages. At this depth (537-851 m), crabs were absent, no fouling was observed and gillnets showed no signs of damage even after long soak times. Hence, the only efficiency reduction to these gillnets is presumably due to the weight of the catch itself which forces headline height to decrease, and when fish fall off the nets may rise again to continue the cycle. Our results are supported by others, e.g. fleets with soak time of 1 year contained approximately 90 kg of groundfish per net during retrieval cruises at depths of 290-310 m. 20-30 miles off Cape Bonavista, Newfoundland, where the presence of crabs was minimal (unpublished data, Fisheries and Marine Service, Canada). In a study by the Irish Sea Fisheries Board (unpublished), gillnets in 80 m of water suffered much less fouling than inshore gillnets (15-18 m) and continued to be more effective in catching fish for longer.

It is not possible to accurately determine catch rates at long soak times without visual observations or tagging catches while gillnets are still deployed (Kaiser et al., 1996). Working at great depths introduced methodological challenges, particularly due to the problem of making visual observations. A study in the Bay of Biscay (Puente et al., 2001) was methodologically similar to our experiments. Like us, these authors classified their catch according to its condition and compared catches of fresh fish in ghost nets with catches of fresh fish at commercial soak times. However, their results clearly differed from ours (see below).

The quality classification is crucial because counts of fish in stages 5–7 of decomposition are not reliable indicators of actual catches. During fishing trials at the Norwegian coast only 15% of the catch registered by ROV was retained after hauling, due to losses of decaying fish (author's observations, unpublished data). The decrease in total catch after 7 and 10 days (Fig. 3), when an increase would have been expected (cumulative catch can never fall in theory), is probably due to the disintegration of soft body parts that causes fish to fall out of the net either at the seabed or during hauling. The correspondence in frequency distribution at similar soak times (see Fig. 2), confirms that the criteria for the different stages are appropriate and demonstrates the replicability of the method. By determining the difference in efficiency between nets fished for extended and commercial soak times and multiplying this factor by the commercial catch rate, the "ghost fishing" catch rate can be estimated. This method may also be used to calculate changes in catch rates over time before stabilization, but the importance of this short period will decrease at long soak times. Catches taken after stabilization will primarily affect the cumulative catch.

The results show that individual fish could deteriorate completely within a 24-h period, due to the activity of fish lice. The bacterial decay rate was not determined in this experiment, but other findings have shown a lower rate of deterioration as temperature decreases (Groenewold and Fonds, 2000) and, hence, a low rate of decay is likely in the Greenland halibut fishery. The way in which the fish were caught (89% wedging) may postpone the start of this process since fish may remain alive after capture (the capture process does not affect operculum movement). Exactly for how long fish may stay alive in the net is not known, but the rapid increase of dead fish (stage 4, Fig. 2) between 9 and 10 days in experiment 2 may be the result of exhaustion and death of wedged fish.

During the first 4 months of ghost fishing, Puente et al. (2001) found similar catch rates in ghost and commercial fleets, while after 6 and 12 months, ghost fleets had completely ceased to catch monkfish (*Lophius piscatorius, L. budegassa*). Carr and Cooper (1987) estimated that groundfish gillnets with a soak time of at least 4 years (most of them probably 7 years or older) would catch 15% of commercial catch rates, on the basis of data on reduced vertical profile, fouling and net integrity. Bech (1995) found during a retrieval cruise at Ilulissat Kangia (North Greenland) that of 12 recently lost gillnet fleets, the efficiency of four fleets had fallen to 75%, seven had fallen to 25% and one had stopped fishing. The catch rates estimated in our study (28-43 and 67-100 kg/fleet/day), the continued catches of the target species (20-30% of commercial catch rates, Fig. 4) and the large number of nets retrieved every year (106-1180, unpublished data, Norwegian Directorate of Fisheries) suggest a significant unaccounted mortality in the Greenland halibut stock. However, these figures (especially catch rates) should be treated with caution, and are only valid during the experimental periods, because of seasonal and annual variation in fish concentrations. Large variations in catches have also been observed during retrieval cruises. In that respect, more comparisons of commercial and ghost nets should be made, taking into account both the temporal and spatial envelope of the halibut fishery. Data from 2002 trials showed the same trend of stabilising catches at 20-30% that of commercial also after 100 days, while the catch rate were different from the ones reported here (author's observations).

The low number of peer reviewed reports, lack of standardized methods and often highly site-specific results means that general conclusions must be drawn carefully. However, some general features specific for deep-water ghost-fishing gillnets have been demonstrated. Breakdown of nets is slow, and in the absence of crabs and fouling organisms at this depth the only efficiency reduction to gillnets seems to be the catch itself which reaches an equilibrium after a short time. The great depth also excludes any influence of bad weather. This confirms the general concern that ghost fishing in deep water is a more serious problem than in shallow water (Breen, 1990), and suggests that captures of target species may continue for long periods beyond the experimental duration, albeit at a lower rate. In addition, the methods are simple and can probably be used in other deep-sea areas where ghost nets are a problem.

In order to fully evaluate the extent of the problem, quantitative estimates of number of lost nets are needed (Chopin et al., 1996). Interviewing fishing vessel skippers about lost nets in conjunction with retrieval cruises has brought promising results in that respect (this was also suggested as a useful approach by Erzini et al. (1997)), and hopefully we will soon be able to provide minimum estimates of annual losses in Norwegian waters.

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