Catching – and Releasing – Cod

Researchers from the Institute of Marine Research in Norway present the results of a study to regulate catch size using dynamic catch control devices.

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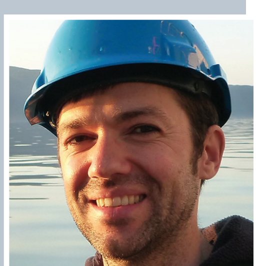

Dr. Shale Rosen

Who should read this paper?

Research in this paper is of value to commercial fishers, managers, and researchers interested in catch control, fish behaviour, and bycatch reduction in demersal seine and trawl fisheries.

Why is it important?

This work focuses on limiting catch sizes by inserting an "overflow valve" to release excess fish to avoid accidental extreme catches. The innovative part relates to utilizing the forces acting on the fishing gear; large, longitudinal openings are cut in the gear and the drag from the codend keeps them closed. When catches build up, the codend expands and (1) opens the gaps in a lateral direction and (2) chokes a fish lock (non-return valve) to inhibit fish from floating out the large openings at the surface.

The ability to design a fishing gear which limits catches to the desired amount has important advantages for fish welfare, quality, safety, and maximizing the value of landings while reducing the instances of discarding at sea. It contributes to quality improvement, which in turn should increase the value of the fish and, thereby, revenues. Excessive catches also result in burst codends and broken gears, which is costly and imposes safety risks. In addition, fishing mortality due to broken gear and discarding reduces long-term yield from fish stocks.

About the authors

Dr. Ólafur Arnar Ingólfsson is a scientist at the Institute of Marine Research in Norway. He has a background as a fisherman and netmaker, and studied fisheries science at the University of Akureyri, Iceland, and the University of Bergen, Norway; he received his doctorate degree in 2006. His research focuses largely on developing technical solutions for catch control, bycatch reduction, and size selectivity in trawl and demersal seine fisheries. **Dr. Odd-Børre Humborstad** is a principal scientist at the Institute of Marine Research in Norway. He studied fisheries biology at the University of Bergen, Norway, and received his doctorate degree in 2004. His research focuses largely on the development of effective, sustainable, resource, and environmentally friendly fishing gear and techniques. **Dr. Keno Ferter** is a senior researcher at the Institute of Marine Research in Norway. He studied fisheries biology and management at the University of Bergen, Norway, and received his doctorate degree in 2015. His main research interests are bycatch survival and fish welfare in recreational and commercial fisheries, tagging of different marine fish species, and catch estimation and management of recreational fisheries. **Dr. Shale Rosen** is a scientist at the Institute of Marine Research in Norway. He studied fisheries biology at the University of Bergen, Norway, and received his doctorate degree in 2013. His research focuses on trawl and optical sampling equipment for fisheries surveys and gear modifications to reduce bycatch in commercial trawl fisheries.

DEVELOPMENT AND EVALUATION OF DYNAMIC CATCH CONTROL DEVICES IN THE DEMERSAL SEINE FISHERIES FOR COD *(GADUS MORHUA)*

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ABSTRACT

Catches of Northeast Arctic cod (*Gadus morhua*) far beyond the vessel's capacity have in recent years led to challenges for Norwegian demersal seine fishers. Consequently, there has been a need for technical solutions for regulating catch size. The aim of this study was to find an operational solution that could rapidly be introduced into the fishery to solve this pressing challenge. In a fishing trial on Norwegian fishing grounds in March 2014, four dynamic catch control devices (DCCD) for demersal seines were tested on board a commercial fishing vessel: Three 1 m diamond holes cut in the top panel (A), rectangular opening with 1 m "bars" made of twines (B), rectangular opening covered with loose nylon netting (C), and two 1.75 m long openings, three meshes wide (D). Depth loggers and underwater cameras were mounted on the DCCD devices and the number of fish escaping at seabed, lower pelagic, upper pelagic, and surface zones were counted. Solution D (two 1.75 m long "slots") performed best as a commercial fishing solution as fish did not begin to escape until the codend was filled. The other solutions released fish before the target amount was in the codend or when the codend became twisted. A not insignificant proportion of the released fish escaped in the upper pelagic zone and at the surface, leading to concerns about barotrauma and other sources of mortality which are discussed.

KEYWORDS

Danish seine; Scottish seine; Catch limitation; Escape mortality; Fish lock

INTRODUCTION

Owing to current high stock levels of Northeast Arctic cod (*Gadus morhua*) along the Norwegian coast and in the Barents Sea, demersal seine fishers often catch more fish than their vessels can safely take on board or process in an effective manner. Breakage of cranes, winches, ropes, etc. have posed safety risks for the fishers and if fish are left for long periods on deck, death by asphyxiation and lack of proper bleeding and gutting results in poor quality [Digre et al., 2010; Borderias and Sanchez-Alonso, 2011; Rotabakk et al., 2011].

During haulback, the risk of burst codends are a concern because of potential high mortality of surface "escapees" due to barotrauma [Humborstad and Mangor-Jensen, 2013] and avian predation. Also, one of the principal markets for demersal seine-captured cod is capture-based aquaculture [Ottolenghi et al., 2004], where it is essential to minimize capture related stressors. These include uncontrolled ascent and subsequent barotrauma [Humborstad and Mangor-Jensen, 2013], pressure damage from compression inside the net, and overall handling time. The risk and severity of these stressors increases with increasing haul size and may lead to higher mortality [Suuronen et al., 2005; Olsen et al., 2013] and poor quality [Margeirsson et al., 2007].

Fishers have reported that modifying fishing strategies to avoid areas with high concentrations of fish, using shorter ropes, reducing tow duration, and minimizing encircling area have failed to sufficiently reduce catches. Therefore, there is a pressing need to develop a solution that regulates the amount of fish retained in the seine, while releasing excess fish unharmed. Catch sensors, which monitor the expansion of meshes in the codend in response to the accumulation of fish, are successfully used by trawlers in order to monitor catch accumulation in the codend and to evaluate if the trawl should be retrieved. These systems work when the entrance of fish can be stopped, for example, by lifting a trawl off the seabed where fish are present. In demersal seining, however, much of the catch enters the codend late in the towing phase and during haulback, as the ground ropes are winched in and herd fish into the seine. In addition, Norwegian demersal seiners frequently use rope lengths in excess of 2,000 m, which is beyond the current range for the trawls' sensors and renders the use of such sensors infeasible.

Dynamic catch control devices (DCCDs) are systems that change the structure and functioning of the gear during the fishing operation so that the gear stops collecting fish when the desired amount of fish has been retained by the gear and actively releases excess fish [ICES, 2013]. Grimaldo et al. [2014] tested DCCDs aimed at the Barents Sea cod trawl fishery. They found that two side cuts along the codend to release excess fish once the codend was full were a better alternative than detachable codends.

To the best of our knowledge, no attempts have hitherto been made to control catches in demersal seines. Technology developed for bottom trawl may not be of use in demersal seines (e.g., catch sensors) due to their different capture principles. Demersal seines encircle the capture area [Nédélec and Prado, 1990] and the catch size depends on fish aggregations and the size of the area encircled. Rope length and geometry of the set are determined when the gear is set out, making the catch amount, to a large extent, determined by the volume of fish initially encircled. Once the capture process is started, it is a predetermined continuous operation with little opportunity to perform catch regulating changes. Restricting the amount of fish entering the seine is not feasible: the solution has to be a method whereby excess fish are released with minimal stress and physical injury.

Our main objective was, therefore, to find an operational solution that could rapidly be introduced into the fishery to solve this pressing challenge. We tested four different solutions of codend cuts and openings, with the aim of finding solutions that would (1) consistently regulate catch size, (2) release fish after preset catch is obtained, (3) favour ease of implementation for the fleet and fisheries regulations, (4) secure high probability for post-release survival, and (5) minimize stress and sublethal effects on released fish.

MATERIALS AND METHODS

Fishing trials were conducted on fishing grounds off Lofoten and Finnmark, Norway, on March 4-16, 2014, on board the demersal seiner MS *Fugløyhav*. Eight hauls yielding data suitable for analysis were conducted over the course of five days of fishing. The demersal seine used was of conventional four panel design, 126 m stretched circumference opening and 138 m stretched length (74 m wings and 54 m belly). Mesh size in forepart of the wings was 300 mm (diamond), reducing to 138 mm in the aft belly. The codend, 130 mm diamond mesh 100 meshes in circumference, was 15 m in length and attached directly to the aft belly. A seine of this size would typically have two 15 m extensions in front of a 15 m long codend, i.e., a total length of 45 m. This presents a large volume where fish can accumulate during haulback without entering the codend. Therefore, the trials were carried out without extensions. The complete catch limitation system consisted of three principal components: a section with release openings for release of surplus fish (the DCCD), a fish lock to prevent fish within the scope of the target catch size from entering the release opening area during haulback, and a choking strop to vary the capacity of the codend to match the target catch size (Figure 1).

Release Openings

Sections with four different DCCD solutions were made and inserted one at a time between the seine belly and the codend. The sections consisted of double diamond meshes of 5 mm polyethylene twine, 145 mm mesh length, 19.5 meshes long, and 60 meshes wide including selvedges. The placement of the DCCD section foremost in the codend was chosen to let out fish as early in the process as possible and to allow for the use of the choking strop as described below. All of the DCCD solutions tested utilized openings in the top panel. The four DCCD solutions were as follows (Figure 2):

A) Three 1 m diamond shaped openings made by removing seven meshes in AB direction. The meshes are intended to open more as catch builds up and increases stretch in the lateral direction of the tow direction.
B) Rectangular opening, seven meshes in

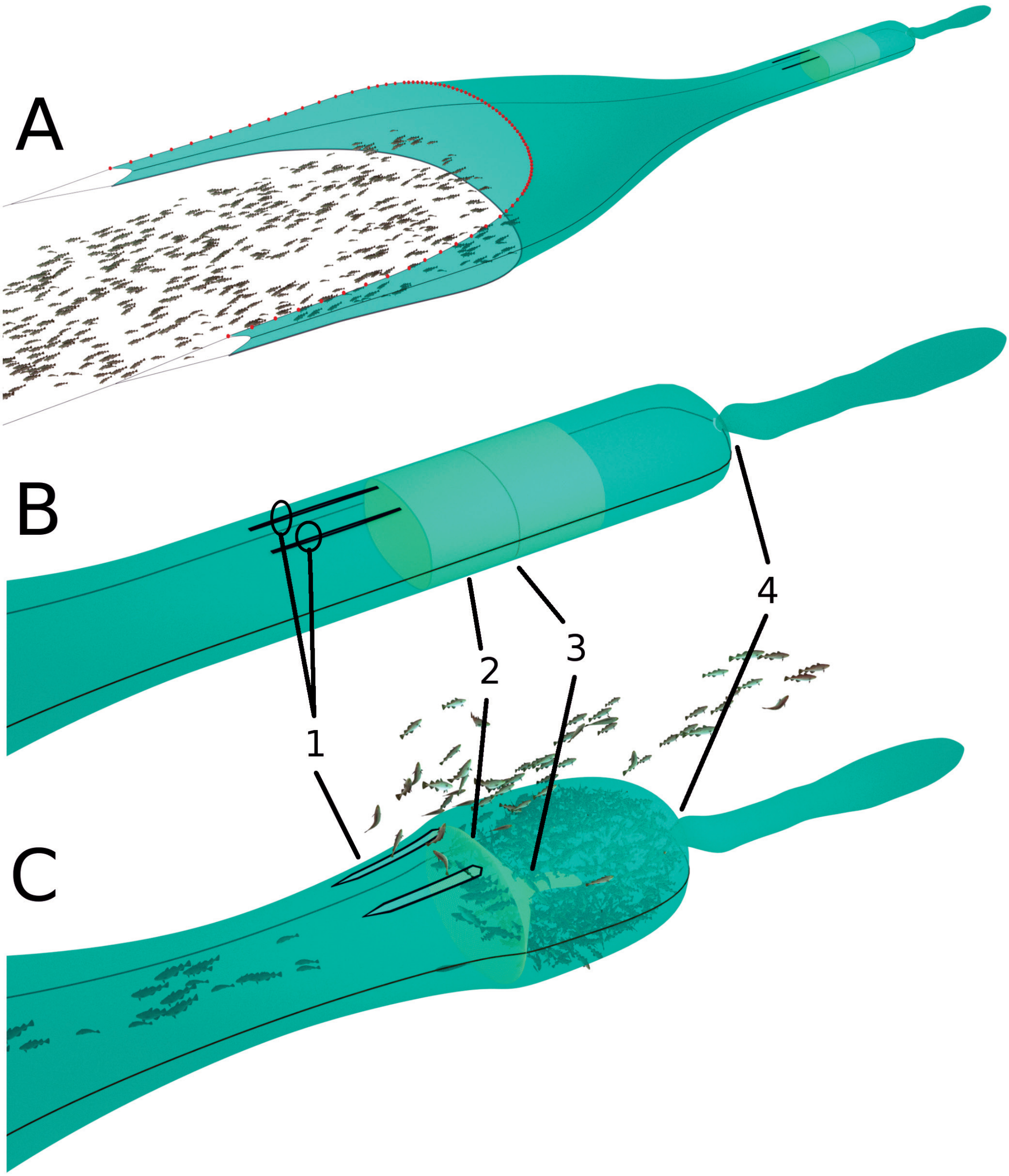

Figure 1: Schematic of a demersal seine, showing where the dynamic catch control devices (DCCDs) were mounted (A) and aft part of the seine net showing the DCCD, fish lock, and choking principle before (B) and after (C) the codend is filled up and expanded. The figure shows solution D, where two longitudinal hexagonal openings (1), a fish lock (2) with choking rope (3), mounted behind the DCCD openings to keep fish trapped in the codend, preventing them from passing forward to the escape openings during haulback and at the surface. To adjust catch sizes, the codend was choked (4) behind the joining of the catch control section and the codend.

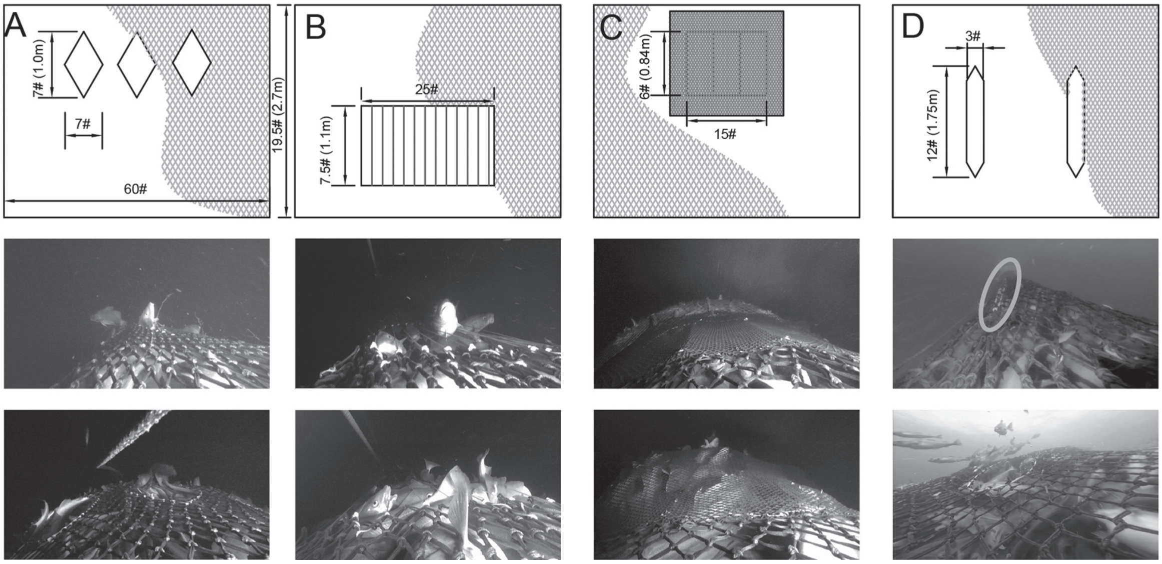

Figure 2: The four different dynamic catch control device (DCCD) designs (A-D) tested and their intended function. The top row shows the schematic of the four DCCDs, the mid row shows photos of the DCCDs from early in the tow when release of fish is not intended, while the bottom row shows the DCCDs late in the tow after the desired amount of fish is achieved in the codend and full release is intended. Solution A: 1 m long diamond meshes. Solution B: Longitudinal nylon twines, forming "twine bars." Solution C: Nylon cover is joined to the netting panel in front of the rectangular opening and covers the opening. Solution D: Longitudinal openings/cuts, 3.5 m in circumference, with 3.15 m (10% shorter) twine threaded along the edges.

length and 25 meshes wide with 5 mm nylon twine tied every second mesh along the seine's longitudinal direction in every second mesh, 5% shorter than the netting. This results in a rectangular opening with longitudinal "bars." The "twine bars" are intended to increase their parallel distance and to open more as catch builds up and increases stretch in the lateral direction of the tow direction.

C) Rectangular opening, six meshes long and 15 meshes wide, covered with loose 50 mm nylon netting attached only at the leading edge to provide a visual barrier which excess fish can nonetheless push through. Two 10 mm longitudinal ropes were added to maintain the opening's shape and support the nylon netting.

D) Two hexagonal openings, 15 meshes long and three meshes wide, three bars cut out in front and rear to form pointed ends. Nylon twine (8 mm) was threaded through the meshes along the circumference of the opening and sized to be 10% shorter than the circumference to ensure that the edges remained stretched and the holes closed until the codend began to fill up and exert latitudinal pressure on the meshes. Due to the shorter twine, the openings are narrow slots in the beginning of the tow, before build-up of catches, and open as catch builds up. The build-up of catch increases lateral stretch and, thereby, mesh opening. The mesh length in the longitudinal direction then reduces, releasing the strain on the nylon twine along the edges.

Fish Lock

A fish lock was mounted behind the DCCD openings to keep fish trapped in the delimited volume between the DCCD and the codend and prevent fish from passing forward to the escape openings during haulback and at the

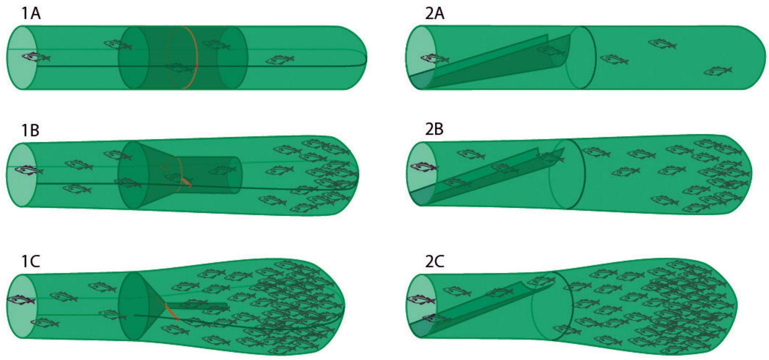

Figure 3: The two fish locks that were used. On the left (1), a fish lock is shown, consisting of a netting cylinder, 3 m long with the same circumference as the codend and a choking rope. The choking rope has a length equal to 25% of the stretched meshes of the cylinder and is threaded through the meshes of the netting cylinder and fastened to the selvedges on each side (1A). As the catch builds up, the codend expands laterally, pulling the rope and closing the fish lock (1B and 1C). On the right, (2) a fish lock of conventional type is shown; an inclined panel of polyethylene netting hampers the return of fish from the codend.

surface. Two different versions of fish locks were used. For all but the last hauls (Haul 8), a funnel-shaped lock was used based upon an inclined netting panel. This panel, 1.5 m long, was joined mesh by mesh to the bottom and in an incline along sides of the codend, leaving an opening at the top which fish could pass through (Figure 3: 2A-C). In this way, fish entering the codend would follow the incline up to the opening. For fish already in the codend, the panel is blocking the return, and they would be guided down, to where the panel was joined to the bottom panel of the codend and offered no route of escape.

For Haul 8 we used a different fish lock, consisting of a 3 m long netting cylinder, with the same circumference as the codend (100 meshes), joined mesh by mesh in front. A 3.75 m choking rope (25% shorter than the stretched meshes) is threaded through the meshes 1.5 m from the front and fastened to the codend selvedges (Figure 1: B3, C3; Figure 3). Before the codend fills up, the rope is slack (Figure 1: B3; Figure 3: 1A), but when the codend expands, the rope chokes the netting cylinder and activates the fish lock (Figure 1: C3; Figure 3: 1B-C).

Choking Strop

Behind the fish lock, the codend was choked with a strop made from 16 mm rope, threaded through the meshes at the selvedges. To adjust catch sizes, the codend was choked either 10, 5.5, or 4.5 m behind the joining of the catch control section and the codend. The choking strop was tied using a conventional codend knot (but without weaving the end of the rope through the final loop). The free end was then tied to a mesh farther forward on the codend and released when the codend came alongside of the vessel during heaving, allowing the catch to move back into the "unchoked" portion of the codend and for the seine to be emptied in the vessel's standard manner.

Data Collection

Date, position, and water depth were recorded for each set. The setting time of the net, start of hauling, start of heaving, and time when the bridle brackets were in the towing blocks were also registered (Table 1). For recording catch quantity, the number of times the codend was emptied to the fish bin was recorded, where one codend corresponds to approximately 1.5 tonnes of ungutted fish. A depth sensor (RBR DR-1060, www.rbr-global.com), with accuracy of ±0.25 m, was attached to the DCC and set to log time-referenced depth continuously every 10 s throughout the trip.

Haul no.	Date	DCC	Rope length (m)	Start towing		Start hauling		Stop hauling	Retained catch (tons)
				Depth (m)	Time	Depth (m)	Time	Time	
1	05.03	A	2420	152	16:14	152	16:53	17:23	30
2	13.03	B	1540	183	06:17	128	06:41	06:59	6
3	13.03	B	1540	110	09:20	110	09:43	10:01	6
4	13.03	C	2420	203	17:02	203	17:42	18:11	7
5	15.03	C	2420	247	08:59	176	09:40	10:15	4.5
6	12.03	D	1540	146	11:24	88	11:43	12:00	6
7	12.03	D	1540	187	14:53	121	15:13	15:30	7.5
8	15.03	D	1540	165	17:18	174	17:41	17:58	12

Table 1: Fishing depth, rope lengths, tow time, and catches of cod for the experimental hauls with the four dynamic catch control systems (DCCDs) tested.

Escapement from the various catch-control solutions at the surface was evaluated by direct visual observations from the vessel during the final stages of haulback and as the catch was taken on board. Their performance during the process of towing and hauling was assessed using video footage gathered from an action camera (GoPro Hero 3) in a waterproof housing, with two 7 w red (620 nm) LED light tubes positioned 0.5 m in front of the openings. Cod have low spectral sensitivity for light waves above 600 nm [Anthony and Hawkins, 1983]; therefore, the 620 nm light used is assumed to have minimal effect on their behaviour.

The number of fish escaping through the different DCCDs were counted from video footage and categorized according to release depth. In this respect, demersal means fish released before haulback when the seine is still in contact with the bottom; lower pelagic is the lower half of the water column; upper pelagic is the upper half of the water column; and surface is defined as fish released after the seine net initially breaks the surface during heaving.

A total of eight hauls were conducted and filmed with the four concepts, one with solution A, two with each of solutions B and C, and three with solution D. For estimating the total weight of released fish, we assume their average weight to be equal to that of landed fish (average of 4.8 kg, round weight).

RESULTS

All the DCCD concepts were functional in terms of limiting catch quantities (see video animation: www.youtube.com/watch?v=b621WuOINUw). Total retained catch for the eight hauls was 79 tonnes, with 68 tonnes released. However, the depth at which fish were released (demersal, lower pelagic, upper pelagic, and surface) varied considerably between DCCDs and hauls (Table 2). When the escape openings were open throughout the whole catch process, as for solutions A and B, fish were lost before the codend was filled, i.e., required catch quantity was achieved.

Solution A: three 1 m uncovered diamond openings did not fulfill requirement number two that fish be released after the requisite

DCC	Haul	Choking rope placement (m)	Catch retained (tons)	Catch released						
				Total		Zone (%)			
				tons	%	Demersal	Lower pelagic	Upper pelagic	Surface
A	1	10	30	18.4	38	97	1	1	1
B	2	4.5	6	6.3	51	35	24	24	17
	3	4.5	6	7.1	54	29	49	22	0
C	4	4.5	7	2.5	27	39	23	38	0
	5	5.5	4.5	11.2	71	41	20	22	17
D	6	4.5	6	7.7	56	18	33	17	33
	7	4.5	7.5	6.7	47	29	29	29	14
	8	5.5	12	8.4	41	27	41	19	13

Table 2: Catch retained and released for the four different dynamic catch control devices (DCCDs). Release is based on counts of escaping fish observed from video and converted to metric tonnes using a mean weight of 4.8 kg per individual fish (average weight of landed fish). Choking rope placement is the distance from the fish lock to the choke.

amount of catch had been captured. This resulted in the highest proportion of fish escaping at the fishing depth. The loss of fish, however, before the codend was filled led to the conclusion that this was not a satisfactory solution that fishers would adopt. Therefore, only one trial with this "wrong track" solution was conducted.

Solution B: a rectangular opening with "twine bars" also worked for limiting catch sizes. But like solution A, fish were lost early in the catching process. In addition, fish that contacted the longitudinal "bars" of nylon twine bars crosswise tended to get stuck, blocking the opening and preventing other fish from exiting.

Solution C: a rectangular opening covered with netting also resulted in catch losses early in the towing and when catches were low. This was partly caused by twists in the aft portion of the seine net which resulted in the opening being oriented towards the seabed, during which the netting fell down leaving the opening wide open.

Solution D: two parallel splits were closed early in the capture phase due to the longitudinal stretch in the seine and shortened twines along the openings, and no fish were observed to escape. When the codend expanded longitudinally due to build-up of catch, the splits gradually opened and excess fish were released. Maximum opening was observed when hauling of the ropes started, and fish were released continuously as the codend ascended.

DISCUSSION

DCCD Functionality

The four solutions tested all released excess fish, but their performance against the five preset aims varied. Devices A, B, and C all have the drawback that great amounts of fish are released for various reasons before the codend fills up. The adoption of those designs will result in economic losses for the fishers at lower catch rates when catch regulation is not needed, and likely additional fishing activity (more sets or setting over a larger area) with associated additional seabed impacts and fossil fuel emissions. Further, the implementation and ability to enforce standard rigging of solutions B and C was judged as non-optimal and more difficult than A and D. Design D, two elongated hexagonal openings, stayed closed irrespective of partial codend twist and began to release fish only after the codend was nearly filled up. For these reasons and the simplicity of the system with respect to implementing it in existing demersal seine gear and enforcing its design, solution D was introduced into fisheries regulation as of January 1, 2017 [Norwegian Directorate of Fisheries, 2016]. There are, however, issues with this DCCD solution with regards to survival and possible sub lethal effects (aims 4 and 5), most notably (but not limited to) barotrauma, gear contact, and swimming stress that all contribute to overall stress [Davis, 2002] and increased susceptibility for delayed mortality (see detailed discussion below). Moreover, fish locks configuration plays a role in terms of surface release. The fish lock in use by fishers varies as some use netting cylinders and others use netting funnels or panels, as shown in Figure 3: 2). While the fish lock has negligible impact on DCCD performance during hauling, it plays an important role at the surface. The fish lock is supposed to hold fish inside the codend even without any water flow. The fish lock with the inclined netting panel did hold fish sufficiently inside the codend, resulting in fish passing out of the codend and forward. In some cases, this resulted in fish floating out of the openings of the DCCDs at the vessel's side. However, an improved fish lock version (Figure 3: 1) consisting of a 3 m long mesh cylinder with a choking rope activated as the codend fills has been implemented together with design D [Norwegian Directorate of Fisheries, 2016; see also animation URL listed under "Results"].

Effects on Released Fish

While solving the problem of huge catches by release of excess fish, we introduce another issue that needs to be addressed; the fate of the escapees. The main stressors associated with the capture phase of demersal seining are physical contact, prolonged forced swimming, and decompression stress during ascent from depth [Humborstad and Mangor-Jensen, 2013]. These stressors can lead to mechanical injuries/wounds, exhaustion, and barotraumas that isolated or cumulatively affects the post release fish [Davis, 2002].

Abrasions from contact with the gear are unlikely to result in immediate mortality for the released fish [Soldal et al., 1993]; however, high incidence of skin infection in Baltic cod has been associated with escape from trawls [Mellergaard and Bagge, 1998]. During release in DCCD systems, physical contact is probably lower than via mesh or grid selectivity [Suuronen et al., 2005; Ingólfsson et al., 2007] since the release holes are large relative to the fish. Build-up of catch and contact with the gear in front of the fish lock was, however, occasionally seen and crowding is believed to cause net abrasion as fish adjacent to the netting are forced against the twine [Digre et al., 2010]. Although we overall suspect the level of abrasion to be low, the release could be made even less abrasive by using knotless twine in the net in front of the fish lock and the edges of the release openings themselves.

It has been shown that fish may die from exhaustive exercise [Beamish, 1966; Wood et al., 1983], especially in less robust species like haddock [Breen et al., 2004]. Trawling for longer than four hours has also been shown to influence the survival rate of captured cod [Olsen et al., 2013]. However, no escape mortality of Atlantic cod penetrating codend meshes and sorting grids has been observed at tow speeds of ~1.7 ms^{-1} (3.5 knots). Therefore, mortality due to exhaustive exercise is unlikely the case in demersal seine fisheries where the towing and heaving phases are relatively short (on the order of 0.5-1.5 h, Table 1) and at low speed, typically 0.5-0.8 ms^{-1} (1-1.5 knots). In areas where catch rates are particularly high (where DCCDs would be used), fishers will typically encircle a relatively small area, minimizing the duration of towing and heaving. Thus, the fatigue-related stress inflicted by swimming inside demersal seines seems unlikely to inflict post release mortality.

One of the main issues with the use of DCCD design D (the preferred design) is that 40% of the fish were released in the upper pelagic and at the surface. While surface release can be reduced by improved fish lock design, release in the upper pelagic is still an issue of concern. Fish with closed (physoclistous) swimbladder (e.g., all gadoid species) will experience barotrauma when they are brought up from deeper water due to the expansion of gas inside the swimbladder when ambient pressure is reduced (Boyle's law). One barotrauma effect is that some fish become positively buoyant which would cause them to float at the surface and be exposed to avian predation [Milliken et al., 1999]. In addition, the gas expansion can lead to internal injuries (e.g., swimbladder rupture and gas bubble formation in the blood system) and external injuries (e.g., exopthalmia and skin bubbles), which may have lethal and sublethal impacts [Humborstad et al., 2016; Ferter et al., 2015; Midling et al., 2012; Humborstad and Mangor-Jensen, 2013]. In the case of cod, saithe (*Pollachius virens*), haddock (*Melanogrammus aeglefinus*), and whiting (*Merlangius merlangus*), the swimbladder ruptures at approximately 70% pressure reduction relative to acclimation depth [Tytler and Blaxter, 1973; Humborstad and Mangor-Jensen, 2013]. Assuming that the capture depth also is the depth of neutral buoyancy, this means that fish released in the upper pelagic and surface most likely would have punctured their swimbladder. Ferter et al. [2015] investigated barotrauma in hook-and-line caught cod. They found all cod that were brought up to the surface from deeper than 20 m had a swimbladder rupture and most of these cod also had gas bubbles in their blood system. When these fish were re-submerged to capture depth at a rate simulating the cod's natural descent, no short-term mortality was observed. Similarly, experiments on escape mortality of cod and haddock escaping at the surface from demersal seine showed that none of the cod and less than 10% of the haddock died [Soldal and Isaksen, 1993]. To increase the proportion of fish escaping at depth, larger and/or more openings could be used. We only tried openings in the top panel, while fish experiencing pressure reduction would likely seek downwards. Therefore, additional openings at the bottom panels also would be likely to elicit greater escape at depth.

While lethal impacts seem to be negligible, there is still a potential for short- and long-term sub-lethal impacts due to barotrauma. Midling et al. [2012] and Humborstad and Mangor-

Jensen [2013] showed that the swimbladders of cod heal rapidly and regain function soon after rupture. During this healing process, however, behavioural changes have been observed for cod and other species. Both Northeast Arctic cod [van der Kooij et al., 2007] and Pacific cod (*Gadus microcephalus*) [Nichol and Chilton, 2006] return to shallower water depth after an initial escape dive, and only return gradually to capture depths while their swimbladder is filled with gas (recuperation period). Thus, even though the cod may survive after they have passed the fishing gear and managed to escape through the DCCD in the upper pelagic, such behavioural changes could, for example, cause reduced reproductive success if this happens during a spawning season. Moreover, barotrauma leads to long-term effects in snapper (*Chrysophrys auratus*), e.g., damage of the gonads which again can reduce reproductive success [Peregrin et al., 2015]. The problem of too large catches is most notably a feature during the seasonal fisheries when cod are migrating to spawning grounds, during spawning, and on post spawning migrations back to feeding areas. Given the uncertainty of inflicted behavioural changes and potential direct effects on gonads, it is recommended that future work should focus on increasing the proportion of fish released at capture depth and in the lower pelagic to avoid negative impacts of barotrauma. When the pressure reduces during ascent, it would be natural reaction for physoclistous fish to seek down. Therefore, perhaps the most obvious improvement to test would be to insert escape openings in the bottom panel in addition to those in the top.

Our results are based on hauls with high availability of fish at the fishing grounds and the desired catch amount was retained. The gradual expansion of the slots, however, means that some fish will be lost before the required maximum amount is achieved, which would be undesirable on lower availability fisheries. The regulations put into force in January 2017 permit the use of DCCD, but it is not mandatory, and fishers have to evaluate the need for the catch limitation device. Despite the possible issues of delayed and unaccounted mortality for the escapees discussed above, we believe the use of catch control devices is warranted in circumstances where the alternatives in these cases are potentially worse (i.e., risk of codend bursts and fisher's safety, incentives to discard excess catch).

Limitations and Later Work

The authors recognize there are several limitations of this study. Firstly, this was a preliminary study and few replicate hauls were made. Also, while we believe that the scale of the catch sizes is correct, we were unable to accurately weigh the fish. In addition, we were in a situation where we had to work simultaneously on improvements of both escape solutions and fish locks. Differences in fish lock across experimental treatments is, of course, not optimal. Due to these merits, statistical treatment of the data has its limitations.

Later work on the solution in collaboration with fishers and the Norwegian Directorate of Fisheries has resulted in a solution that has been adapted and proven to be successful. All fishers who have reported problems with the use of the DCCD system have either used codend extension in front of it, or codends of dimensions greater than the DCCD. Therefore, the DCCD is described in the fisheries regulations [Norwegian Directorate of Fisheries, 2016] and its use regulated by the Directorate of Fisheries. The sizes of the openings must be at least 2 m and as close to the fish lock as possible. The use of ultra-high-molecular-weight polyethylene (e.g., Spectra or Dyneema) is encouraged along the escape openings, as early release of fish has been associated with stretching of the ropes/twines (we used 8 mm nylon which presumably stretches over time). No straight-cut codend extensions are allowed in front of the DCCD. Long (15-45 m) extensions result in fish entering the codend late, unpredictable catch sizes, and considerable amount of fish have been observed floating at the surface. Also, it is essential that the circumference of the codend matches the circumference of the DCCD. Some of the demersal seiners use codends with circumference of ~10 m. In line with the use of long codend extensions, large circumference codends in combination with narrower DCCDs has resulted in unpredictability of catch sizes and substantial amount of fish floating at the surface. In addition, large codend circumference makes it difficult to limit catches accurately, as a cylinder of 10 m circumference holds ~8 m^3 per m length. For choking the codend, an automatic releaser has been developed [Ingólfsson et al., 2021; see also animation URL listed under "Results"]. The releaser is mounted on the codend with a choking strop to limit its volume during fishing. At a pre-set depth during ascend (usually 30 m), the choking strop is automatically released by the releaser, the codend volume increases, the escape openings close, which in turn inhibits further escape at surface. Also, onboard taking is simplified as manually removing the choking strop is not needed.

CONCLUSION

The catch control system recently introduced in the demersal seine fisheries for cod in Norway was selected based on evaluating and balancing criteria of function, fish impact, and ease of implementation. Currently, the system chosen scores high on function and ease of implementation. Uncertainty with regards to especially barotrauma effects, however, calls for continued research focusing on increasing the proportion of excess catch released early in the towing and haulback phases when the codend is still at the capture depth. During periods of high availability, DCCDs are advocated, as the alternatives in these cases are likely worse both for the safety of fishers and contributions to unreported and unaccounted mortality.

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