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Assessment of cod survival in the Irish fly-shoot seine fishery using survivorship pop-up satellite archival tags

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ABSTRACT

Fly-shoot seining for demersal species is a commercially important fishery for Irish vessels operating in the Celtic Sea. We conducted a pilot-scale assessment of cod (*Gadus morhua*) survival in the fly-shoot seine fishery using survivorship pop-up satellite archival tags (sPATs). Supporting information on fish condition including vitality on a modified four-point scale - excellent, good, poor and moribund - was collected for all cod caught during the trial. Ten cod of suitable size for tagging ($\geq$ 55 cm) in excellent and good vitality were tagged and released. Cod in poor and moribund vitality were assumed to have died. A Kaplan-Meier estimator was used to assess cod survival. Of 96 cod caught during the trial, 53 (55%) were $\geq$ 55 cm with 18 (34%) of these found to be in excellent or good vitality. Tagged fish were representative of the latter component of the catch. All 10 tags reported data with tag deployment period ranging from 2 to 21 days and a mean survival of 10 days. Assuming a 34% survival probability at time zero, survivability gradually decreased to zero at day 20 when all fish were assumed to have died. Barotrauma was likely the main cause of poor survival in this study. Alterations to fishing operations to reduce barotrauma are technically feasible but unlikely to be commercially viable. The sPATs and tagging procedures used in this study generally worked well in estimating cod survival rates, elucidating mortality causes and have potential applications for other species.

1. Introduction

Poor stock status has led to parts of the Celtic Sea having no directed fishery permitted for Atlantic cod (*Gadus morhua*) where the quota is exclusively for bycatches in fisheries for other species (EU, 2020). Irish fishers need to reduce cod catches to help improve stock sustainability and avoid early cessation of fishing operations under the European Union (EU) landing obligation.

Bottom-trawlers can use raised fishing line gear (McHugh et al., 2017) or change fishing grounds to avoid cod in the Celtic Sea. Fly-shoot seiners (SSC) do not have this gear option, and limited grounds suitable for seining are available outside the Celtic Sea which restricts their movements.

Irish fishers reported that seine-caught cod are in excellent condition and requested an assessment of post-capture survival towards application for an exemption under the EU landing obligation (LO). Findings from previous research on pacific cod (*Gadus macrocephalus*) (Nichol and Chilton, 2006) and lab-based experiments on Atlantic cod (Tytler and Blaxter, 1973) suggested that cod caught in the Irish seine net fishery would likely be subject to barotrauma and poor post-capture survival. However, no direct observations of Atlantic cod survival from fly-shoot fisheries were available. Hence, we determined that a pilot-scale study would help provide new information on Atlantic cod survival, determine the feasibility of further large-scale work, point to potential alterations in fishing practices to boost survival, while also satisfying industry requests for assessment of cod survival in the specific fishery.

Survival studies conducted under the LO have mostly involved captive observation where fish caught under conditions representative of normal fishing practices were monitored in containment facilities (e.g., Uhlmann et al., 2016; Van der Reijden et al., 2017; Fox et al., 2020). This approach facilitates direct observations of fish mortalities and potential underlying causes such as injuries associated with the capture process. Mortality estimates derived from captive observations can be

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prone to bias. Capture-induced stress and mortalities (e.g., Snyder, 1975; Portz et al., 2006) can lead to overestimated mortalities while protection from predators associated with containment can lead to underestimates (e.g., Raby et al., 2014; Breen and Catchpole, 2021). Also, captive monitoring is challenging for species such as cod due to their morphology and swimming behaviour.

Tagging methods can also be used to assess post-capture survival, can be particularly useful for larger species, and in taking account of predation mortality (e.g. Morfin et al., 2019). Mark and recapture or recovery techniques can require large-scale studies to tag and recover enough fish, and tag reporting is not always consistent raising uncertainty over mortality estimates (e.g. Pollock et al., 2001). Inferring survival from acoustic telemetry techniques is challenging due to potential non-detection of tagged individuals which leave the detection area, and the risk of confounding detections of dead with live individuals (Morfin et al., 2019).

Used extensively in studies on fish behaviour, pop-up satellite archival tags (PSATs) have more recently been used to assess fish survival (e.g., Knotek et al., 2019; Nielsen et al., 2018). They neither require fish recapture nor constrained detection areas to obtain fish survival information. PSATs can, however, be relatively expensive to purchase and large in size compared to the species of interest. Also, benefits in relation to better accounting of post-release predation are less clear due to potentially inflated predation associated with irregular post-release behaviour (e.g., Cosgrove et al., 2015; Hoolihan et al., 2011).

Taking the pros and cons of these different survival assessment methods into account, the PSAT technique best suited our pilot-scale assessment of post-capture survival of cod from the Irish fly-shoot seine fishery. Resulting detailed behavioural observations are discussed in relation to fish survival and potential method-induced mortality.

2. Methods

2.1. Fishing operations

The MFV Róise Catriona, a 24 m steel fly-shoot seine (SSC) vessel caught the cod during commercial fishing operations off Irelands southwest coast in ICES divisions 7.j.g between the 20th – 23rd July 2022 (Fig. 1). The vessel targeted mixed demersal fish using a fly-shoot seine constructed from polyethylene twine with rope ground gear and a 100 mm T90 cod end. This fishing operation encircles fish by deploying port seine ropes which are attached to flotation buoys and payed out until the seine net is set. The starboard seine ropes are then payed out until the port rope is picked up and hauling can commence. Once hauling commences, the seine ropes gradually come together as the vessel moves slowly forward into the tide. Further details on the gear used are provided in Table 1. Data were recorded on operational parameters that could affect survivability such as depth, haul duration and total catch weight for each haul.

Table 1
Gear characteristics.

Gear type	Seine
Sweep length (m)	55
Headline (m)	60
Footrope (m)	68
Fishing circle (No. Mesh × mm)	480 × 120
Seine rope length (m)	2860 × 2
Seine rope diameter (mm)	32
Codend	T90
Nominal mesh (mm)	100
Measured mesh (mm)	109
Length (no. meshes)	49.5
Circumference (no. meshes)	80

2.2. Catch sampling and condition assessment

All cod were caught and handled under normal commercial fishing operations. Catches were landed directly into a holding hopper, transferred to a conveyor and sorted by species during net redeployment or when fishing had ceased. All cod caught during the trip were measured, weighed and condition assessed. Air exposure was recorded from when the cod were first taken aboard until they were condition assessed.

The condition assessments followed guidelines developed by the ICES Guidelines on Methods for Estimating Discard Survival (Breen and Catchpole, 2021). For vitality assessments, we modified the approach from Benoît et al. (2010) to categorise visible barotrauma consisting as partial or full bloating as major injuries instead of minor injuries (Table 2) thereby precluding such fish from tagging. This follows on from research on capture-based aquaculture of cod where such fish are removed during catch sorting as they are considered poor survival candidates (Humborstad et al., 2009).

Injuries and reflexes were assessed to provide further information on fish condition and potential factors affecting survival. Injuries were scored as 1 = present or 0 = absent for each cod (Catchpole et al., 2015; Randall et al., 2021). Reflexes impairments were scored as 1 = absent if a weak or no response was obvious during assessment, and 0 = present if a vigorous response was shown during assessment (Catchpole et al., 2015; Humborstad et al., 2009). Summed injury and reflex impairment scores were divided by the total number of cod sampled to derive proportional occurrence across all sampled fish (Tables 7 and 8).

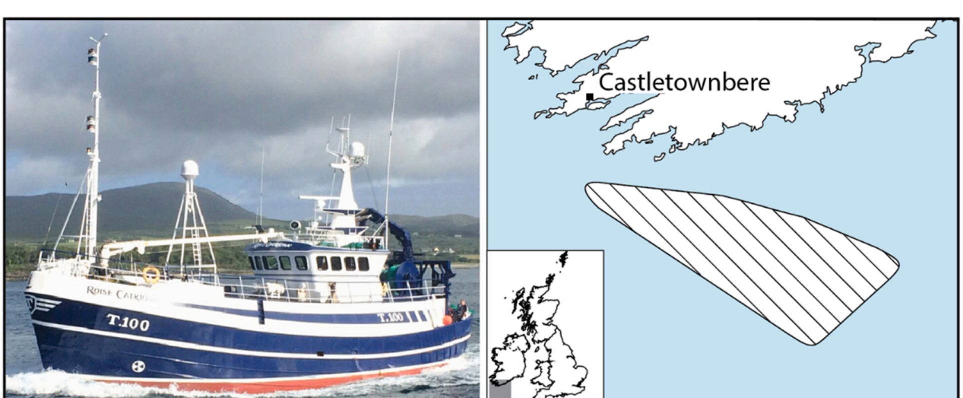

Fig. 1. Study vessel and study location (hatched area).

Table 2
Vitality categorisations modified from Benoît et al. (2010).

Vitality	Abbreviation	Description
Excellent	1	Vigorous body movement; no or minor[a] external injuries only
Good	2	Weak body movement; responds to touching; minor[a] external injuries
Poor	3	No body movement but fish can move operculum; minor[a] or major[b] external injuries
Moribund	4	No body or operculum movements (no response to touching)

([a]) Minor injuries were defined as minor bleeding, or minor tear of mouthparts (≤10% of the diameter), or minor surface abrasion. ([b]) Major injuries were defined as major bleeding, or major tear of mouthparts, or major surface abrasion, or partial or full bloating.

2.3. Animal ethics statement

The Irish Health Products Regulatory Authority (HPRA) ensures that procedures involving the use of scientific animals follow legislative requirements in EU Directive 2010/63/EU and Irish Statutory Instrument No 543 of 2012. We conducted tagging work under HPRA authorisation (Licence No.: AE19121/P003).

2.4. Cod tagging procedure

Wildlife Computers (Seattle, USA) supplied ten survival pop-off archival transmitting tags (sPAT) which record data for a maximum of six days prior to pop up. Tags were set to pop up after a maximum of 30 days deployment or prior to this if vertical movement was restricted for > 24 h; the tag floated at the surface; or depth variance did not exceed 2 m e.g., the fish stayed on the seabed. The latter criteria were used to determine when mortality occurred.

We restricted tagging to cod in excellent (V1) or good (V2) condition. Due to a relatively high tag cost, for the purposes of this study, it was assumed that cod in poor (V3) and moribund (V4) condition died, resulting in a conservative survival estimate.

We chose a minimum length of 55 cm or 2000 g for tagging. This follows advice from Wildlife Computers that these sPATs which are 60 g in air should weigh less than 3 – 5% of fish body weight. It also corresponds to the median size of cod caught by the Irish seine fleet (Pers. Comm Irish Marine Institute). Hence, if the survival study were successful, any application for a survival exemption would be restricted to fish ≥ 55 cm. One fish < 2000 g was tagged due to low numbers of fish suitable for tagging.

The tagging procedure closely followed the method outlined in O'Neill et al. (2018). Following biological and condition assessment, cod were placed in 310 L holding tanks with a flow through of fresh seawater prior to tagging periods of up to 15 min. This allowed some time to prepare for tagging and to further monitor fish condition before release. When ready for tagging, anaesthesia was induced by immersing the cod in a smaller 70 L tank with a mixture of seawater and tricaine methane sulfonate (MS-222). Once equilibrium was lost and gill rhythm was slow but constant, the cod was placed dorsal-side up into a lined cradle with a damp cloth placed over the eyes. A constant flow of seawater/MS-222 mixture was pumped across the gills during the tagging procedure.

The sPAT was attached to the fish using a bridle system similar to that outlined in O'Neill et al. (2018). Rubber-backed plastic mounting plates were placed on the fish musculature between the first and second dorsal fin. Spinal cannulae needles were inserted through the plates and musculature, with the inserts of the needles then being removed. Sterilised 0.9 mm stainless steel wire was passed through the needle hollows and the needles then withdrawn. The wire was then tightened by hand on both sides of the fish and the wire ends cut and folded in place to prevent unravelling (Fig. 2). An additional Floy tag was applied to the bridle to allow for further identification.

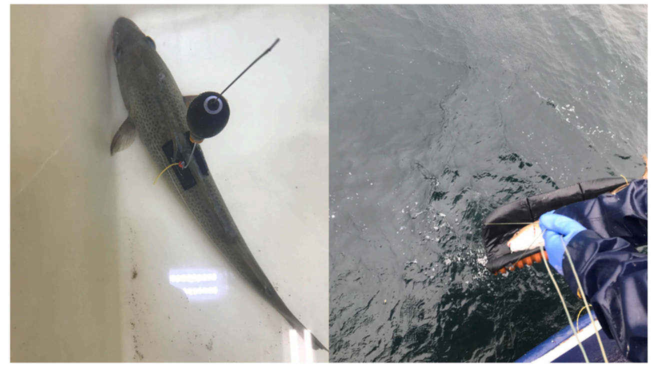

Fig. 2. Cod with bridle system in situ (left) and tagged cod being released from the vessel (right).

The tagged specimen was then placed into another 310-litre holding tank with fresh seawater flow-through and allowed to recover from the tagging procedure. Once equilibrium had returned and gill rhythm was regular and strong, the fish was released from the stern of the vessel using a cradle lowered to the water's surface (Fig. 2).

2.5. Survival analysis

Survivability analysis was conducted using a Kaplan-Meier (KM) estimator which approximates survival probability over time. Calculations and graphic outputs were completed using the R statistical program (4.2.0) with the "survival" package. A survfit function was constructed assigning the time argument to the number of days alive. The KM estimator plot was used to assess survival of cod ≥ 55 cm with V3 and V4 cod assumed dead at time zero. The number of days alive was calculated by deducting one day from the total tag deployment period to take account of the last 24 h when mortality occurred in line with the criteria described above.

2.6. Environmental data

Data on environmental parameters that could affect cod condition at haul level were also recorded. The skipper recorded swell height (m), wind speed (knots), and sea surface temperature (°C). Additionally, air temperature (°C) was recorded using a digital thermometer and bottom water temperature (°C) using data storage tags (DSTs) which were attached to the headline of the seine net and set to record every 10 min (Table 9).

3. Results

A total of 19 hauls were conducted over four consecutive days fishing. The main commercial species caught were hake (*Merluccius merluccius*), haddock (*Melanogrammus aeglefinus*), megrim (*Lepidorhombus whiffiagonis*), and monkfish (*Lophius piscatorius)*. Unwanted catches consisted of lesser spotted dogfish (*Scyliorhinus canicula*), grey gurnard (*Eutrigla gurnardus*), European squid (*Loligo vulgaris*), and boarfish (*Capros aper*) (Table 3).

Mean towing speed was 1.06 kt. Haul duration ranged from 02 hr 10 min – 03 hr 25 min with a mean of 02 hrs 26 mins. Bottom fishing depths ranged from 93 to 118 m with a mean of 107 m. Bulk catch per haul ranged from 83 to 717 kg with a mean of 335 kg. Cod catches ranged from 1 to 11 individual cod per haul (Table 4).

Of the 96 cod caught during the trial 53 (55%) were ≥ 55 cm with 18 (34%) of these found to be in V1 or V2 condition (Table 5). The survival probability at time zero was 34% in line with the latter observation. The survival probability dropped to 21% between days 5 and 10, 10% on day 13 and gradually decreased to zero at day 20 when all fish were assumed to have died (Fig. 3). The mean survival period of tagged fish was 10

Table 3
Species catches.

Species	Weight (kg)
Hake (*Merluccius merluccius*)	2150
Haddock (*Melanogrammus aeglefinus*)	1130
Megrim (*Lepidorhombus whiffiagonis*)	650
Unwanted catches	589
Monkfish (*Lophius piscatorius*)	500
Plaice (*Pleuronectes platessa*)	300
Whiting (*Merlangius merlangus*)	277
Lemon sole (*Microstomus kitt*)	275
Cod (*Gadus morhua*)	248
Skates and rays (*Rajiformes*)	80
John Dory (*Zeus faber*)	80
White pollack (*Pollachius pollachius*)	40
Red gurnard (*Aspitrigla cuculus*)	25
Red mullet (*Mullus Barbatus*)	20
Total catch	6364

days.

Tagged cod ranged in length and weight from 59 to 100 cm and 1850 – 11,980 g. Air exposure for tagged cod ranged from 4 to 16 min. Tag deployments ranged from 2 to 21 days (Table 6). Six fish demonstrated bottom-orientated and four fish surface-orientated behaviour prior to tag pop off (Fig. 4).

Net marking was the most common injury type followed by full or partial bloating related to barotrauma. Righting was the most impaired reflex (Table 8).

The weather was calm to fresh throughout the study with swell heights ranging from 0.3 to 2.1 m and wind speeds of 6 – 21 knots. Sea surface temperature was relatively high as expected for the month of August while bottom temperature was > 3 °C cooler than surface temperatures. Air temperature inside the shelter of the vessel was 18 °C during the study (Table 9).

4. Discussion

Study results suggest poor cod survivability in the Irish fly-shoot seine fishery. Elevated levels of visible barotrauma resulted in just 34% of ≥ 55 cm cod assumed to have initially survived the capture process. Representative of this catch component, tag data demonstrated

Table 5
Summarised cod vitalities.

Vitality	Count (n)	Proportion (%)
≥ 55 cm		
1	11	21
2	7	13
3	28	53
4	7	13
Total	53	100
< 55 cm		
1	4	9
2	4	9
3	11	26
4	24	56
Total	43	100

Table 4
Summary fishing operation, cod catch and tag data.

Haul ID	Date	Haul duration (hr: min)	Bottom Depth (m)	Bulk catch (kg)	Swell Height (m)	Wind speed (knots)	Cod (n)	Tagged cod (n)	Average survival (days)
1	20/07/2022	02:20	111	83	2.1	21	3	-	-
2	20/07/2022	02:20	111	320	1.9	16	2	-	-
3	20/07/2022	02:15	111	333	2.0	16	5	1	13
4	20/07/2022	02:15	111	467	1.7	16	7	1	20
5	20/07/2022	02:25	111	264	1.7	16	6	-	-
6	20/07/2022	02:10	111	290	1.6	10	1	1	11
7	21/07/2022	02:20	97	277	1.0	6	4	2	3.5
8	21/07/2022	02:20	97	365	0.5	6	10	1	5
9	21/07/2022	02:30	93	467	0.7	6	4	1	17
10	21/07/2022	02:35	93	198	0.4	6	9	-	-
11	21/07/2022	02:30	98	243	0.3	6	2	1	1
12	22/07/2022	02:30	108	355	0.6	6	2	2	13.5
13	22/07/2022	02:10	109	544	0.6	6	5	-	-
14	22/07/2022	02:35	109	234	0.8	10	4	-	-
15	22/07/2022	02:05	109	397	1.1	10	1	-	-
16	22/07/2022	02:20	109	186	1.2	10	3	-	-
17	22/07/2022	03:25	109	430	1.3	10	2	-	-
18	23/07/2022	02:45	118	192	2.0	16	5	-	-
19	23/07/2022	02:25	118	717	2.0	16	11	-	-

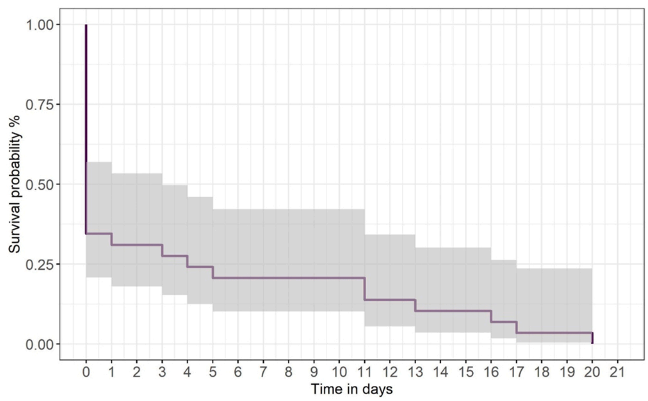

Fig. 3. Kaplan-Meier estimator for cod ≥ 55 cm.

an average survival period of 10 days, while the KM estimator demonstrated 10% survival probability after 15 days and 0% survival probability after 20 days. Generally, a minimum survival probability of 50% after 15 days or longer is needed before a case can be made towards a survival exemption so results fell well short of that level.

It is possible to reduce barotrauma and physical stressors in seine caught cod by reducing hauling speeds and using canvas lining in the codend, as evidenced by the results observed in a Norwegian fishery (Dreyer et al., 2008). The latter is a highly specialised operation, however, which targets cod for capture-based aquaculture and it would be difficult to implement such measures in the Irish wild-capture fishery: cod are not a target species and a canvas lining would greatly reduce size selectivity for all species. Also, the Irish fishery is relatively deep (mean bottom depth 106.5 m). At these depths cod would require more than 10 hr decompression time to avoid rupturing the swim bladder (Nichol and Chilton, 2006; Tytler and Blaxter, 1973). The net took ~ 20 min to travel from seabed to the surface during the current study. Some increase in this hauling period would be possible but extending to > 10 h would not be commercially viable in the Irish fishery.

Results of the latter studies suggest that all cod caught during the current study suffered barotrauma which was simply not visible for fish in excellent or good condition. Cod can recover from barotrauma if they can submerge quickly and are not negatively impacted by other injuries e.g., in recreational fisheries (Ferter et al., 2015a). Cumulative impacts including barotrauma, physical stressors in the codend, air exposure, and injuries observed under commercial fishing conditions in the seine fishery are likely, however, to have negatively affected cod survival in the current study.

Observed behaviour in some of our sPAT tagged cod was consistent with barotrauma: Behaviour patterns attributed to barotrauma have been observed in pacific cod (*Gadus macrocephalus*) tracked with data storage tags (DST). These often include an initial escape dive to the bottom, followed by a quick return to shallow water, and a gradual descent back to the bottom (Nichol and Chilton, 2006). The 10 sPAT tags restricted data collection to the 6 days prior to pop off but 4 of these were deployed for ≤ 6 days permitting observations of initial diving behaviour.

With the exception of one fish which likely died almost immediately, all of these fish displayed surface-orientated behaviours more consistent with barotrauma than the normal bottom-orientated behaviour associated with Celtic Sea cod (Neat et al., 2014): Fish 8 likely died soon after release given a rapid descent to the bottom followed by minimal variance in depth and pop-off in less than 2 days. Fish 4 initially exhibited a typical barotrauma response with an escape dive to the bottom followed by a gradual ascent to depths < 25 m but subsequently failed to return to the bottom with tag pop-off occurring after > 24 h floating at the surface. Fish 5 remained at shallow depths before pop-off at the surface. Fish 6 remained shallow for almost 2 days before conducting several bounce dives in quick succession to greater depths followed by a period in shallow water before pop-off (Fig. 4).

Longer term tag deployments (Fishes 1, 2, 3, 7, 9 and 10) all returned to deeper depths. Although > 2 m (the threshold for pop-off), minimal differences in depth occurred over the 6 days prior to pop-off for all except Fish 9 (Fig. 4). It is possible that some of these fish were dead during this period with movements from tidal cycles and currents preventing tag pop-offs.

Tag pop-off on Fish 9 occurred after a return to diel migratory behavior consistent with vertical depth preferences of Atlantic cod (Ferter et al., 2015b) and likely recovery from barotrauma. For the purposes of the current survival study we assumed that this fish suffered delayed mortality. The reason for this delayed mortality is unclear but Nichol and Chiltion (2006) also observed delayed mortality of a cod which recovered from barotrauma for unknown reasons. It is also possible that Fish 9 was still alive but did not alter its swimming depth by > 2 m in the 24 h prior to pop-off. Hence, this pop-off may be an artefact of our tag programming but, as outlined above, a greater pop-off threshold might have caused issues in relation to non-detection of mortalities from tidal movements.

Stress associated with carrying sPAT tags may have been partly responsible for tagged fish mortalities. PSATs have been successfully deployed for extended periods in behavioural studies on other species of a comparable size such as European eel (*Anguilla Anguilla*) (Wright et al., 2022), and Atlantic salmon (*Salmo salar*) (LaCroix, 2013) so its unlikely that the tagging method was directly responsible for poor cod survival in the current study. As outlined above, a variety of combined stressors likely caused mortalities, and we cannot discount the possibility that sPATs contributed in this regard.

Control fish which been subject to reduced stressors e.g., caught in recreational fisheries or aquarium acclimatised fish can be useful in elucidating method induced mortality associated with monitoring survival (Catchpole et al., 2015; Breen and Catchpole, 2021). In the current study, this would have required deployment of sPATs on control fish which was not possible due to the cost of the tags and scarcity of recreational-caught cod of a suitable size.

Relatively high-water temperatures during our study may have

Table 6
Tagged cod data.

Fish ID	Start date	Tag release date	Tag deployment period (days)	Vitality score	Size (cm)	Weight (g)	Air exposure (min)
1	20/07/2022	03/08/2022	14	1	61	2215	16
2	20/07/2022	10/08/2022	21	2	59	1850	12
3	20/07/2022	01/08/2022	12	2	71	4135	9
4	21/07/2022	25/07/2022	4	1	100	11,980	10
5	21/07/2022	26/07/2022	5	1	61	2680	15
6	21/07/2022	27/07/2022	6	2	80	6000	8
7	21/07/2022	08/08/2022	18	2	69	4165	8
8	21/07/2022	23/07/2022	2	1	59	2220	11
9	22/07/2022	03/08/2022	12	1	85	6835	4
10	22/07/2022	08/08/2022	17	1	85	6945	8

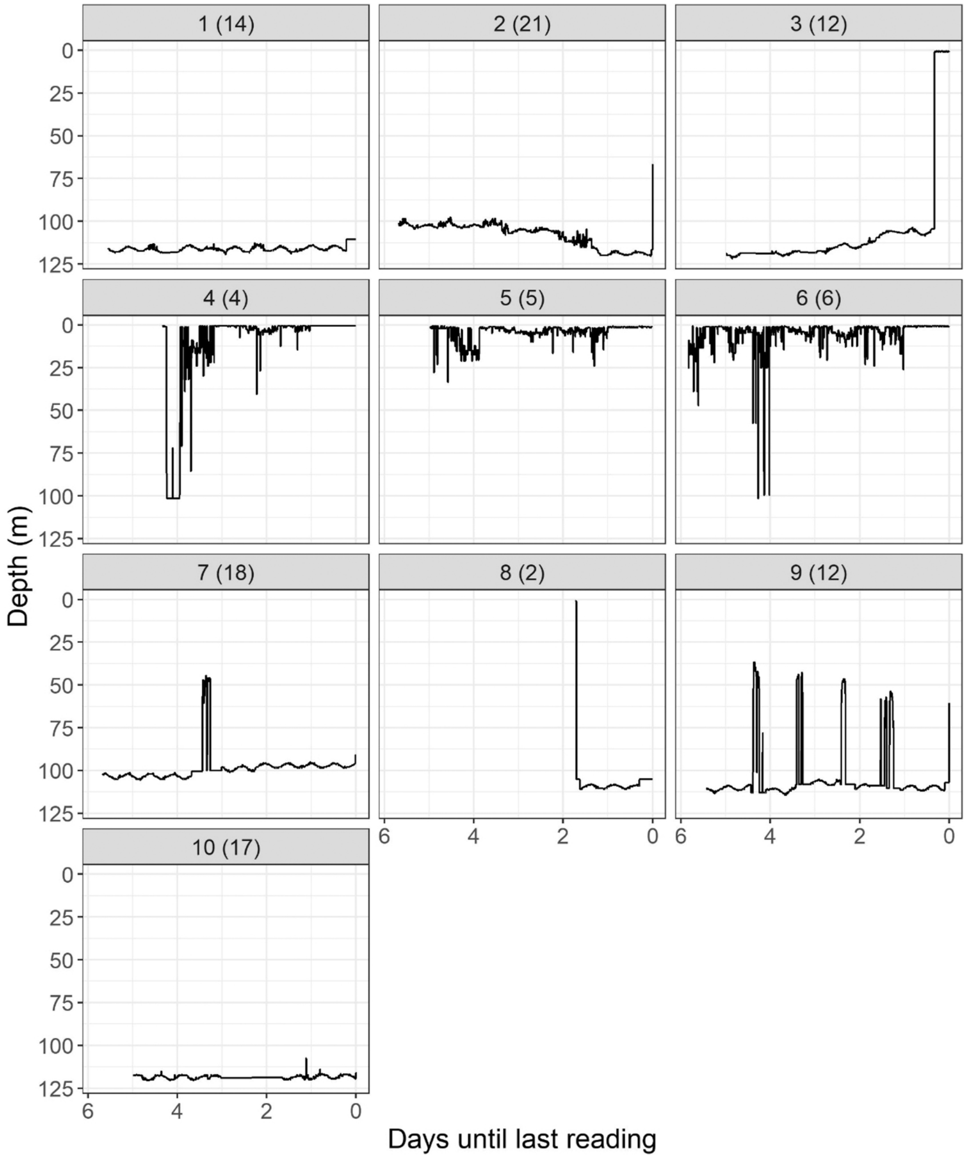

Fig. 4. Vertical behaviour for tagged cod up to six days prior to tag pop off. Figure headings consist of Fish ID with total deployment period in brackets.

affected recovery from barotrauma and contributed to combined stressors. Cod recover from barotrauma by gradually reinflating their swim bladders to attain neutral buoyancy. This is achieved through secretion of gas by vascular structures in the swim bladder, a chemical process which varies with temperature (Scholander, 1954; Van der Kooij et al., 2007).

Previous studies have shown a direct relationship between water temperature and the gas secretion rate (McNab and Mecham, 1971; Harden Jones and Scholes, 1985) so one might expect improved recovery at higher temperatures (Nichol and Chilton, 2006). On the other hand, higher water temperatures have been found to negatively affect post release survival rates and increase stress levels in a variety of fish species (e.g., Gale et al., 2013; Kraak et al., 2018).

It is unlikely that temperature shock negatively affected our cod survival which were subject to a mean difference of 3.3 °C between bottom and surface water temperatures (Table 9). This is well below known daily thermal ranges of up to 13 °C of cod in the North East Atlantic (Righton et al., 2010). The Irish fly-shoot seine fishery operates year-round. Follow up studies in winter months when temperatures are cooler may help elucidate the effects of temperature on cod mortality in this fishery. Insufficient data were available to robustly assess the effects of catch weight on fish survival, but any effects were likely superseded by barotrauma.

Net marking was the main injury observed for all cod but this is considered to have a minor effect on fish condition and survival (Benoît et al., 2010; Humborstad et al., 2009). Full and partial bloating associated with barotrauma were the next most common injury. The ability of cod to right or actively swim into the correct orientation was the highest impaired reflex response across all cod which maybe linked to damage of the swim bladder which is used to control buoyancy. Although some of our sPAT tagged cod displayed behaviour consistent with barotrauma, they did not have visible bloating nor did they suffer from the righting impairment (Tables 7 and 8). This highlights limitations in fish condition assessments for fish prone to barotrauma and supports the need for full-scale survival studies to robustly assess their post-capture survival.

Study results have implications for survival of escapees during bottom fishing. Ingólfsson et al. (2021) demonstrated how around 50% of undersize haddock escapement occurred as the net approached the surface. These fish likely experienced higher mortality due to barotrauma-related stress than fish escaping at the fishing depth during the towing process. Underwater footage of the codend during hauling in the current study confirmed widescale barotrauma in hake (*Merluccius*

Table 7
Proportional injury occurrence across 96 observed cod.

Injury	Description	≥ 55 cm (%)	< 55 cm (%)
Abrasion	Haemorrhaging red area from abrasion.	11	12
Bleeding	Obvious bleeding from any location.	6	5
Bruising body	A body injury to underlying tissues in which the skin is not broken, often characterized by ruptured blood vessels and discolorations	4	9
Bruising fin	A fin injury to underlying tissues in which the skin is not broken, often characterized by ruptured blood vessels and discolorations.	15	12
Fin fraying	Fins damaged, possibly with slight bleeding.	28	37
Internal organs exposed	Internal organs exposed with wounds.	0	0
Net marks	Any type of clearly visible net marks on body from trawl, gillnet, etc.	75	95
Scale loss	Obvious area of scale loss.	62	88
Scratches	Thin shallow cut or mark on (a surface).	15	37
Partial bloating	Abdomen swollen, due to inflated swim bladder, slack to touch, fish floats at surface of tank when not swimming.	32	44
Full bloating	Abdomen swollen, due to inflated swim bladder, tight to touch, fish floats at surface of tank and cannot dive.	30	37
Wounding	Nicks or cuts on body.	6	9

Table 8
Proportional reflex impairment across 96 sampled cod.

Reflexes	Description	≥ 55 cm (%)	< 55 cm (%)
Body flex	Attempts to escape when restrained.	10	50
Evade	Attempts to avoid capture.	50	70
Head complex	Regular pattern of ventilation with jaw and operculum.	0	40
Righting	Returns to normal orientation when turned upside down.	60	80
Tail grab	Burst movement away from tester.	30	60
Vestibular – ocular response	Eyes roll when body rotated around long axis.	10	40

merluccius) our main catch species. Swim bladder rupture was observed when the net reached ~ 20 m from the surface (Fig. 5).

Ingólfsson et al. (2021) recommend the use of codend mesh with the meshes open throughout its length such as T90 mesh to facilitate escapement of fish at depth. T90 mesh has been shown to be highly effective in reducing catches of undersize haddock, whiting and cod in Irish fisheries (Browne et al., 2016; Browne et al., 2019). Further testing of T90 in the seine net fishery by McHugh et al. (2019) and the Irish fishing Industry confirmed benefits in relation to reductions in undersize fish but also demonstrated increases in market sized catches. Consequently, T90 mesh is currently widely used by the Irish seine net fleet which assists in escapement, survival and conservation of undersized fish Table 9.

The sPATs and tagging procedures used in this study generally worked well with all 10 tags successfully reporting data on fish behaviour which greatly assisted in estimating cod survival rates and elucidating mortality causes.

Although numerous survival studies have been conducted in response to the EU landing obligation, further work will likely be needed in relation to vulnerable species such as skates and rays in response to the EU Biodiversity Strategy and new Marine Strategy Framework Development Measures. Testing and development of novel survival assessment techniques such as sPATs will greatly assist in dealing with these new challenges.

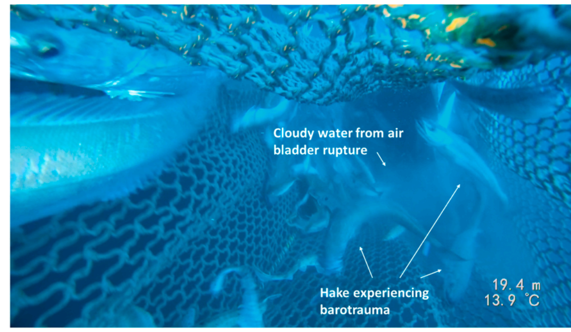

Fig. 5. Bloating and air bladder rupture (cloudy water) in hake (Merluccius merluccius) when the codend reaches ~ 20 m from sea surface.

Table 9
Environmental data collected during the study.

Parameters	Range and mean (in brackets)
Swell Height (m)	0.3–2.1 (1.19)
Wind speed (knots)	6–21 (10.75)
Sea surface temperature °C	14.7–17.3 (16.44)
Bottom temperature °C	10.6–15.6 (13.14)
Air temperature on vessel °C	18

CRediT authorship contribution statement

Martin Oliver: Data curation, Formal analysis, Methodology, Visualization, Writing – original draft, Writing – review & editing. **Ross O'Neill**: Data curation, Methodology. **Shane Murphy**: Formal analysis, Software. **Ronan Cosgrove**: Formal analysis, Methodology, Validation, Writing – original draft, Writing – review & editing. **Matthew McHugh**: Visualization, Writing – review & editing. **Daragh Browne**: Methodology, Writing – review & editing. **Coilin Minto**: Formal analysis, Software.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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