Fisheries Research 285 (2025) 107379

Contents lists available at ScienceDirect

Fisheries Research

journal homepage: www.elsevier.com/locate/fishres

Survivability of spurdog (*Squalus acanthias)* in an inshore otter trawl fishery

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ARTICLE INFO

Handled by: B. Morales-Nin

Keywords:
Condition assessments
Survivorship pop-up satellite archival tags
Survival
Kaplan-Meier estimator
Management scenarios
Trawling

ABSTRACT

Spurdog (*Squalus acanthias*) was previously fished by European Union (EU) vessels, but the fishery closed in 2011 due to poor stock status. Following positive advice on spurdog stock recovery, the fishery reopened in 2023 prompting assessments of management measures and post-capture survival. We assessed spurdog survivability in an inshore bottom otter trawl fishery using condition assessments and survivorship pop-up satellite archival tags (sPATs). We used a five-point scale (excellent, good, poor, moribund and dead) to categorise vitality of 463 sampled spurdog. Twenty spurdog in excellent, good and poor condition were tagged with sPATs. Moribund fish were assumed to have died. Tagged fish size was restricted to 80–100 cm total length (TL) in line with the size of fish capable of carrying tags, the maximum conservation reference size and condition assessments results. The observed fish vitalities were: 9.9 % excellent, 17.3 % good, 34.6 % poor, 38 % moribund and 0.2 % dead. We used a Kaplin-Meier estimator to assess survival of tagged fish over a 30-day period and estimated an overall survival rate of 78 % for spurdog between 80 and 100 cm. Study results provide important input towards enhanced management of spurdog fisheries in the North-East Atlantic.

1. Introduction

Spurdog (*Squalus acanthias*) is a ram-ventilating benthopelgic elasmobranch species which is highly mobile and has been shown to exhibit consistent diel vertical migration (DVM) in depths from 10 – 200 m (Sulikowski et al., 2010; Carlson et al., 2014; Klöcker et al., 2024). The species is widely distributed across the Northeast Atlantic from Iceland to Northwest Africa, occupying water temperatures from 1 – 20 °C (Shepherd et al., 2002). Tagging studies have indicated a single Northeast Atlantic stock although some transatlantic migrations occur (Holden and Meadows, 1964).

Spurdog were formerly fished commercially in Ireland, France, Norway and the UK using trawl, gillnet and long lines (ICES, 2019). In Ireland, gillnet and otter trawl fisheries mainly occurred inshore along the west coast (Fahy, 1988; MI, 2018). A ban on landing spurdog was introduced in European Union (EU) waters in 2011 due to poor stock status and fisheries remained closed until 2023. Following positive advice, the fishery reopened in 2023. In 2024, a total allowable catch (TAC) of 11204 t was provided in International Council for the Exploration of the Sea (ICES) Divisions 6, 7 and 8 with Ireland allocated 1887 t.

A maximum conservation reference size (MXCRS) of 100 cm was established in European Commission (EC) waters to deter targeting of mature female spurdog based on ICES simulations of potential benefits to the stock by protecting mature females. ICES acknowledged that improved estimates of discard survivorship from various commercial gears are required to better examine the efficacy of such measures (ICES, 2019).

Exemptions aside, catches of quota species are required to be retained on board vessels and landed ashore under the EU landing obligation (LO). Once the quota for a particular species has been exhausted, vessels must cease operations in that area raising challenges for fishers and managers in multi-species fisheries (Uhlmann et al., 2019). The Irish fishing industry requested assessments of spurdog survivability towards potential high-survivability exemptions under the LO to help deal with these challenges.

Ellis et al. (2017) outlined limited availability of information on spurdog survival in commercial fisheries. Some short-term survival studies suggest that spurdog is more likely to survive when released post-capture in trawls compared with gillnets. In the UK, 59 % of

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https://doi.org/10.1016/j.fishres.2025.107379
Received 17 October 2024; Received in revised form 27 March 2025; Accepted 15 April 2025
Available online 28 April 2025
0165-7836/

spurdog taken as bycatch on board commercial gillnet fishing vessels were categorised as lively when first taken aboard, 8 % were sluggish, and 33 % were dead when first taken aboard (Bendall et al., 2012). Data from three electronically tagged gillnet-caught fish in lively condition exhibited long-term survival for two fish while one fish died 10 days after release (Bendall et al., 2012). Such delayed mortalities have also been observed in previous survival assessments of cod (*Gadus morhua*) and cuckoo ray (*Leucoraja naevus*) (Oliver et al., 2023; Baulier et al., 2024).

On the US East coast, a 55 % mortality rate was observed for gillnet caught spurdog after 48 hours in captivity in fish cages. No mortalities occurred in trawl-caught spurdog held under the same conditions (Rulifson, 2007). The latter study was conducted during winter months when temperatures, which are generally known to affect fish survival (Gale et al., 2013; Van der Reijden et al., 2017; Kraak et al., 2018), were relatively low. Also, most of the trawl hauls were 30-minute duration in depths < 18 m which likely contributed to the low mortalities observed in that fishery. A further US East coast study assessed trawl-caught spurdog survival in summer months in water depths up to 73 m and observed a 29 % mortality rate after 72 hours captivity in sea pens with total catch weight significantly affecting survival (Mandelman and Farrington, 2007).

Survivability assessments can be conducted using captive observation (e. g., Uhlmann et al., 2016; Van der Reijden et al., 2017; Fox et al., 2020) but may be prone to experimental biases such as capture induced stress and mortality from handling and holding wild fish in captivity (Portz et al., 2006). As a ram-ventilating species, spurdog generally need to swim to breathe although they can sustain short periods of inactivity. While they are stationary, they use buccal pumping as the method of ventilation (Carlson et al., 2004). Kelly et al. (2020) observed an individual spurdog spending sustained periods of inactivity resting on the bottom of a water tank suggesting that the species can continue to breathe while static. However, Mandelman and Farrington (2007) suggested a 24 % observed mortality rate in control spurdog caught using hook and line was potentially caused by captivity in holding pens. No long-term captive holding studies to assess survival of spurdog have been published.

Tagging methods can also be used to assess fish survival. Pop-up satellite archival tags (PSATs) have previously been used to assess post capture survival for species such as blue marlin (*Makaira nigricans*) and blue sharks (*Prionace glauca*) (Graves et al., 2002; Moyes et al., 2006)). These tags transmit data via satellite and do not need to be recovered which makes them ideal for survival studies. More recently Oliver et al. (2023) used specifically designed survivorship pop-up satellite archival tags (sPATs) to assess cod (*Gadus morhua*) survival in an Irish fishery.

We aimed to assess spurdog survival in an inshore bottom trawl fishery in Irish waters. We chose to use sPATs to assess spurdog survival given the successful use of pop-up tags in assessing the survival of other fish species and in monitoring long term behaviour of spurdog (Carlson et al., 2014; Klöcker et al., 2024). We used fish condition assessments to inform our study design and make inference on the survival of non-tagged spurdog. We implemented criteria around tag pop-ups and examined depth data from the tags to help validate survival results. The representativeness of study results to bottom otter trawl fisheries, and application of the developed approach to other fisheries are discussed.

2. Methods

2.1. Fishing operations and catch sampling

Fishing operations were conducted onboard a 12 m commercial otter trawler, the MFV Karen Mary operating off the mid-west coast of Ireland in ICES 7b (Fig. 1) during day trips. The vessel typically targets mixed demersal fish and Dublin Bay prawns (*Nephrops norvegicus*), similar to other inshore trawlers operating along the west coast. Most hauls were conducted in October 2023 but some were also conducted in March and July 2024.

The vessel fished a single-rig otter trawl. The ground gear was constructed of 2” rubber discs in the wings and 4” rubber discs in the bosom. The vessel deployed an 80 mm diamond-mesh codend and 80 mm square-mesh panel in line with legislative requirements (Table 1).

The vessel landed its catch directly onto the deck where the fishermen collected catches of all species in baskets and emptied them onto a sorting table. The scientists aimed to measure, sex and condition assess all spurdog caught except for hauls where it was not practical due to large numbers when spurdog were taken from representative subsamples distributed within the bulk catch. Any spurdog not assessed were counted prior to being retained or released. During hauls which were primarily focused on tagging, we selected fish based on their size and vitality. These fish were measured, weighed, sexed and condition assessed.

2.2. Condition assessments

We used fish condition assessments to inform our study design and make inference on the survival of non-tagged spurdog. The condition assessments followed guidelines developed by the ICES Guidelines on Methods for Estimating Discard Survival (Breen and Catchpole, 2021). Specifically, we assessed vitality based on a combination of reflexes and

Table 1
Vessel and trawl gear characteristics.

Vessel	Karen Mary (DA127)
Length (m)	12
Engine (kW)	150
Trawl type	Demersal fish
Trawl manufacturer	Marine Suppliers
Trawl configuration	Single
Headline length (m)	37
Estimated headline height (m)	1
Footrope length (m)	42
Fishing-circle (meshes × mm)	400 × 80
Number of panels in trawl	2
Nominal codend mesh size (mm)	80

Fig. 1. Trial vessel; MFV Karen Mary, and fishing locations (hatched areas).

injuries using an approach adapted from Benoît et al. (2010), which included a fifth vitality category for dead fish (Table 2).

We conducted more detailed assessment of injuries to provide further supporting information on fish condition based on the protocol from Braccini et al. (2012) (Table 3). We also recorded air exposure for tagged spurdog as the time elapsed from when the codend was lifted out of the water to when each spurdog was condition assessed.

2.3. Animal ethics statement

We conducted tagging work under Health Products Regulatory Authority (HPRA) authorisation (Licence No. AE19121/P003) which cover staff from the Irish Marine Institute to tag specific fish species named on the licence including spurdog. HPRA ensures that procedures involving the use of scientific animals follow legislative requirements under EU Directive 2010/63/EU and Irish Statutory Instrument No 543 of 2012.

2.4. Tagging procedures

Wildlife Computers (Seattle, USA) supplied 20 sPATS 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 depth variance did not exceed two meters for > 24 h e.g., the tag floated at the surface; or the fish died and sank to the seabed.

The sPATs weigh 61 g in air and the tag manufacturer recommended that tags should weigh less than 3 – 5 % of fish body weight. We restricted tagging to spurdog between 80 and 100 cm in line with the MXCRS, condition assessments results and the size of fish capable of carrying tags calculated using season specific length-weight relationship for spurdog (Froese and Pauly, 2024).

We tagged spurdog using a phased approach due to logistical and financial constraints. In phase 1, we tagged 10 spurdog in V1 and V2 condition, and in phase 2 we tagged a further 10 fish in V3 condition. Good fish survival in phase 1 justified further deployment of sPATs and survival assessment of fish in poorer condition. Larger fish > 80 cm formed a minor component of spurdog catches and very few of these fish were categorised as V4. In the interest of having enough fish available for tagging, we chose to exclude V4 fish from tagging and assumed they suffered mortality.

We placed spurdog in 310 litre holding tanks to minimise stress prior to tagging. When ready for tagging, we inserted a hose in the mouth with a free flow of sea water over the gills. Similar to Afonso and Hazin (2014), the head was covered with a damp cloth to help calm the fish and minimise stress and the sPAT was attached to the fish using 500 lb monofilament line fitted through the primary dorsal fin (Fig. 2). An additional Floy tag was applied to the monofilament line to allow for further identification. We released the spurdog headfirst directly over the stern of the vessel at a height no greater than one meter from sea level (Fig. 2).

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

Vitality	Category	Description
V1	Excellent	Vigorous body movement; no or *minor external injuries only
V2	Good	Weak body movements; responds to touching; *minor external injuries
V3	Poor	No body movement; limited spiracular movement; *minor or **major external injuries
V4	Moribund	No movements of body or spiracle, (no response to touching), **major external injuries
V5	Dead	Clear signs of dead fish e.g., rigor mortis, decomposition

*Minor injuries: bleeding, tear/ bruising of fins or mouthparts (≤10 % of the diameter), trawl/ gill-net marks or surface abrasion, all on minor scale
**Major injuries: bleeding, tear/ bruising of fins or mouthparts, trawl/ gill-net marks, or surface abrasion, all on major scale

Table 3
Injury assessments based on Braccini et al. (2012).

Category	Presence of wounds and bleeding
High	1 (no cuts or bleeding observed)
Moderate	0.66 (1–3 small cuts or lacerations not deep only on skin, some bleeding but not flowing profusely, no exposed or damaged organs)
Low	0.33 (>3 small cuts or one severe cut or wound, some bleeding but not flowing profusely, little organ exposure and if exposed organs are undamaged)
Nil	0 (extensive small cuts or very severe wounds or missing body parts, excessive bleeding, blood flowing freely and continuously in large quantities, internal organs exposed and damaged, may be protruding
	Presence of skin damage and surface bruising by physical trauma
High	1 (0 % of skin body damage or bruises or redness)
Moderate	0.66 (<5 % of skin body damage or bruises or redness)
Low	0.33 (5–40 % of skin body damage or bruises or redness
Nil	0 (>40 % of skin body damage or bruises or redness)

Fig. 2. Top: Spurdog with sPAT affixed to primary dorsal fin ready for release, Bottom: spurdog released headfirst into the water.

Mortalities were initially considered to occur when tags popped off prior to 30 days or did not transmit data. We also examined depth data from these tags to assess fish behaviour prior to finalising survival estimates.

2.5. Survival models

We analysed survival of tagged spurdog using the nonparametric Kaplan-Meier (KM) method which approximates the true survival curve with step wise survival over time with uncertainty. The KM approach calculates survival using:

$$\widehat{S}(t) = \prod_{i:t_i \leq t}\left(1 - \frac{d_i}{n_i}\right), \tag{1}$$

Where n_i are the numbers at risk and d_i are the mortalities at time t. For each individual, the time-to-event was the number of days alive with a maximum of 30 days at which time the individual was considered right censored. 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 tag pop-up occurred. Both a base KM fit and a survival model with vitality as a stratum were fitted. Ninety five percent confidence intervals (CI) were calculated on the log-scale. A log-rank test was performed to determine whether there was a difference between the survival curves for the three different vitality categories V1, V2 and V3 tagged fish.

We estimated the overall survival rate for 80 – 100 cm spurdog ($\widehat{S}_{80-100}$) in all vitality categories (V1 – V5) as:

$$\widehat{S}_{80-100} = (1 - p_{80-100, \quad V4V5})\widehat{S}(t = 30) \tag{2}$$

Where $p_{80-100,V4V5}$ was the proportion of 80–100 cm spurdog in moribund (V4) and dead (V5) vitality categories and $\widehat{S}(t = 30)$ was the survival rate of tagged individuals from the Kaplan-Meier survival function (Eq. 1).

Survival models were fit using the R statistical program (4.2.0) with the "survival" package (Therneau, 2023); and graphical outputs prepared using the survminer:ggsurvplot function (Kassambara et al., 2021).

2.6. Environmental data

We recorded data on environmental parameters to facilitate their assessment in relation to survivability. The scientist onboard recorded air temperature (°C) and sea surface temperature (°C) using a digital thermometer. Bottom water temperature (°C) was recorded using data storage tags (DSTs) attached to the trawl. Sea surface water salinity (g/L) was recorded using a hydrometer. The skipper visually estimated swell height (m) and obtained wind speed (knots) from localised weather forecasts. Cloud cover was recording using the okta unit of measurement determined by visual estimation of proportional cloud cover.

3. Results

3.1. Fishing operations

A total of 17 hauls were observed with depth, haul duration and bulk catch ranging from 40 to 43 m, 120–210 minutes and 91–1605 kg. We sampled 463 spurdog out of a of 1651 spurdog taken aboard. Some 71 % of these were females. 428 spurdog were assessed during 13 hauls in October 2023 with most of the remainder assessed in July 2024. The largest bulk catches and spurdog catches occurred in Hauls 17, 12 and 13, during which 17 spurdog were tagged (Table 4).

3.2. Condition assessments

Of the 463 fish assessed, 9.9 % were V1, 17.3 % V2, 34.6 % V3, 38 % V4 and 0.2 % V5 vitality category. Some 62 % of spurdog across all size classes were in V1, V2 and V3 category. The remainder except for one dead (V5) fish were in V4 category (Table 5).

Some 97 % of spurdog between 80 and 100 cm were in V1, V2 or V3 category. The remaining 3 % were V4 with no V5 fish recorded. Some 93 % of spurdog over 100 cm and a total of 73 % of spurdog between 61 and 79 cm were in V1, V2 or V3 category. The majority of fish < 60 cm were in V4 or V5 category (Table 5).

No clear size trend was evident from injury assessments. Eighty to 100 cm fish were among the least injured. Smaller and larger fish were slightly more injured compared with 80–100 cm fish (Table 6). Injuries were generally consistent with vitality scores with more injuries occurring in poorer vitality fish (Table 7).

3.3. Tagging results

Tagged spurdog ranged in weight from 1873 to 3569 g. Air exposure ranged from 5 – 25 minutes (Table 8) with a mean air exposure time of 14 minutes. Tag deployment periods lasted the full 30 days for 16 out of 20 or 80 % of tagged spurdog. We tagged six spurdog in V1 condition and four spurdog in V2 condition. Nine out of ten or 90 % of these tags popped up and transmitted data after the full 30-day monitoring period. No data were received for Fish 10. All nine survivors demonstrated typical DVM (Carlson et al., 2014; Klöcker et al., 2024) by occupying deeper water during daytime and shallower water at nighttime (Fig. 3).

Table 5
Proportional occurrence of spurdog by size class grouped by tagged fish (V1, 2, 3), and assumed mortalities and dead fish (V4, 5).

Size class (cm)	V1, 2, 3 (%)	V4, 5 (%)
< 31	50	50
31–40	30	70
41–50	42	58
51–60	40	60
61–70	66	34
71–80	78	22
81–90	96	4
91–100	100	0
> 100	93	7
80–100*	97	3

*Tagged spurdog size range

Table 4
Fishing operation details.

Haul (ID)	Timing	Haul duration (min)	Depth (m)	Bulk catch (kg)	Total spurdog (n)	Total spurdog assessed (n)	Spurdog tagged (n)
1	Oct 2023	210	43	355	88	34	0
2	Oct 2023	210	43	330	49	44	0
3	Oct 2023	135	42	204	17	17	0
4	Oct 2023	135	43	91	19	17	0
5	Oct 2023	120	43	203	140	85	0
6	Oct 2023	130	43	193	74	49	0
7	Oct 2023	120	43	204	60	60	0
8	Oct 2023	165	43	215	14	13	0
9	Oct 2023	120	43	236	42	17	0
10	Oct 2023	150	43	186	39	11	0
11	Oct 2023	145	43	365	44	25	0
12	Oct 2023	180	43	728	319	26	6
13	Oct 2023	180	43	420	191	30	4
14	March 2024	180	40	200	0	0	0
15	March 2024	180	40	126	4	4	2
16	July 2024	180	40	253	1	1	1
17	July 2024	186	40	1605	550	30	7

Table 6
Mean injury scores of spurdog across all size classes - higher scores equates to fewer injuries.

Size (cm)	Mean wounds and bleeding score (± SE)	Mean skin damage and bruising score (± SE)
< 30	0.66 (0)	0.66 (0)
31–40	0.66 (0)	0.66 (0)
41–50	0.66 (0)	0.66 (0)
51–60	0.64 (0.01)	0.59 (0.02)
61–70	0.59 (0.03)	0.57 (0.03)
71–80	0.69 (0.03)	0.69 (0.03)
81–90	0.77 (0.04)	0.69 (0.05)
91–100	0.74 (0.06)	0.71 (0.06)
> 100	0.58 (0.05)	0.58 (0.05)
80–100*	0.76 (0.03)	0.72 (0.03)

*Tagged spurdog size range

Table 7
Vitality score with associated mean injury scores of spurdog across all size classes.

Vitality	Spurdog (n)	Wounds and bleeding score (± SE)	Skin damage and bruising Score (± SE)
1	46	0.76 (0.03)	0.72 (0.03)
2	80	0.82 (0.02)	0.81 (0.02)
3	160	0.62 (0.008)	0.60 (0.01)
4	176	0.59 (0.01)	0.58 (0.01)
5	1	0.33 (0)	0.33 (0)

Ten spurdog in V3 condition between 80 – 100 cm were tagged. Some 7 out of 10 or 70 % of these tags lasted the full 30-day deployment period. Again, typical DVM was observed for the V3 survivors. No data were received for Fish 12 while tags deployed on Fish 15 and 20 popped off after nine days and four days. Little change in depth occurred for the last day for Fish 15 and the last 3 days for Fish 20. Fish 20 likely died soon after release (Fig. 3).

Twelve sPATs popped up in relatively localised areas within Galway Bay while tags deployed on Fish 3, 9, 13 and 17 popped off in more offshore areas (Fig. 5) where spurdog occupied greater depths (Fig. 3).

3.4. Survival estimates

The KM plot of tagged fish by vitality category showed 83 % (95 % CI: 58.2 % – 100 %) survival of six V1 fish, 100 % (95 % CI: 100 %) survival of four V2 fish, and 70 % (95 % CI: 46.7 % – 100 %) survival of 10 V3 fish after 30 days. V1 and V3 fish had an 83 % and 90 % survival probability on day 1 due to non-reporting tags and associated assumed mortalities. Although two further V3 fish died, the overlap in CI showed no significant different in survival probabilities between vitality categories (Fig. 4a). The results of the log-rank test ($p = 0.48$) showed no significant difference between V1, V2 and V3 survival curves. The overall KM plot of 20 tagged spurdog showed 80 % (95 % CI: 64.3 % – 99.6 %) survival and demonstrated a levelling off or asymptote in survival after day nine (Fig. 4b).

Based on the condition assessments and tagging work, we estimated a survival rate of 78 % for all 80 – 100 cm trawl-caught spurdog based on the 80 % survival rate of tagged fish times the 97 % proportion of V1, V2 and V3 spurdog occurring in this size class (Eq. (2), Fig. 4b, Table 5).

3.5. Environmental data

The weather during the trips was calm to moderate (Beaufort force 0–4) with small swell throughout (~ 1 m). Sea surface and bottom temperatures were lower in March compared to October and July. Air temperature was cooler in March and October. Salinity ranged from 30 – 35 g/L (Table 9).

4. Discussion

We assessed spurdog condition and survivability onboard an inshore otter trawler operating off the west coast of Ireland where directed fisheries for spurdog traditionally occurred (Fahy, 1988). However, large catches of spurdog are known to occur in more offshore locations such as off the coast of Scotland as observed recently under the BATmap project (Bycatch Avoidance Tool using mapping) (Marshall et al., 2021; Pers. Comm. Paul Macdonald, Scottish Fishermen's Organisation). Ideally, spurdog survival studies should be conducted in a range of locations to provide data representative of different catch sizes, fishing operations and habitats, and the broader northeast Atlantic spurdog population.

We demonstrated a 78 % survival rate of spurdog between 80 and 100 cm in the current study. Some 97 % of spurdog in this size class

Table 8
Tagged spurdog data.

Haul ID	Fish ID	Start date	Tag release Date	Tag deployment Period (days)	Fish vitality score	Fish size (cm)	Fish sex (F/M)	Fish weight (g)	Air exposure (min)
12	1	26/10/2023	25/11/2023	30	1	100	F	3569	5
12	2	26/10/2023	25/11/2023	30	2	99	F	3467	8
12	3	26/10/2023	25/11/2023	30	1	84	F	2157	6
12	4	26/10/2023	25/11/2023	30	2	81	F	1941	10
12	5	26/10/2023	25/11/2023	30	2	84	F	2157	15
12	6	26/10/2023	25/11/2023	30	2	84	F	2157	11
13	7	26/10/2023	25/11/2023	30	1	96	F	3172	12
13	8	26/10/2023	25/11/2023	30	1	100	F	3569	7
13	9	26/10/2023	25/11/2023	30	2	89	F	2549	9
13	10	26/10/2023	No data	No data	1	97	F	3268	13
15	11	20/03/2024	19/04/2024	30	3	100	F	3569	25
17	12	10/07/2024	No data	No data	3	87	M	2387	20
15	13	20/03/2024	19/04/2024	30	3	80	M	1873	15
16	14	10/07/2024	10/08/2024	30	3	100	F	3569	18
17	15	10/07/2024	17/07/2024	9	3	100	F	3569	18
17	16	10/07/2024	10/08/2024	30	3	100	F	3569	17
17	17	10/07/2024	10/08/2024	30	3	100	F	3569	18
17	18	10/07/2024	10/08/2024	30	3	94	F	2985	15
17	19	10/07/2024	10/08/2024	30	3	98	F	3366	15
17	20	10/07/2024	14/07/2024	4	3	85	M	2232	15

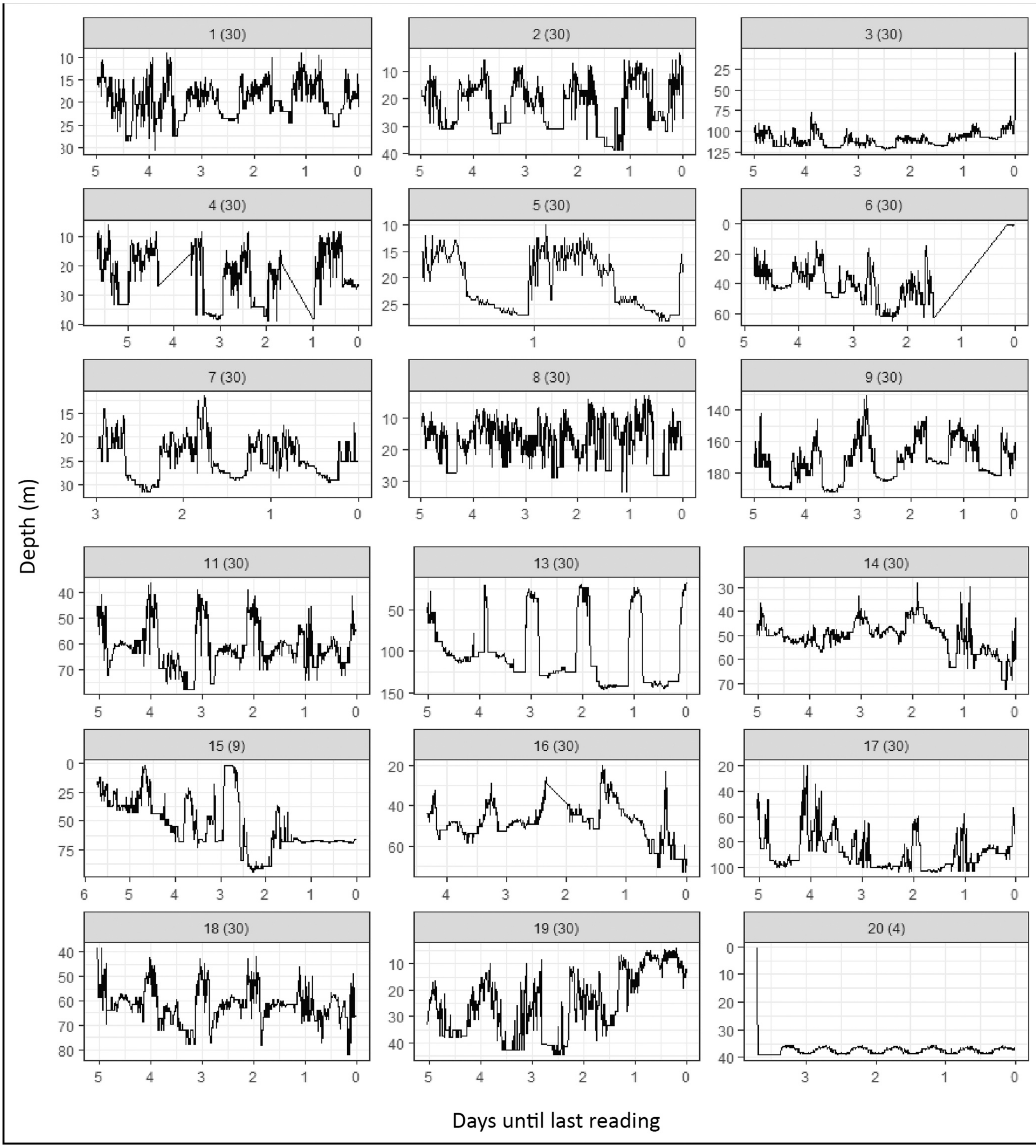

Fig. 3. Diel vertical migration of V1, V2 (Fish 1 – 9) and V3 (Fish 11–20) tagged spurdog in days preceding tag pop-ups. Figure headings consist of Fish ID with total deployment period in days in brackets.

were in excellent, good and poor vitality (V1, V2 and V3). 93 % of spurdog > 100 cm, and 73 % between 61 – 80 cm were also in V1, V2 and V3 vitality. However, these size classes were slightly more injured compared with 80–100 cm spurdog and full-scale assessments would be needed to evaluate their survival. The majority of fish < 60 cm were in moribund vitality.

The sPAT tags used in the current study would be ideal to assess survival of > 100 cm spurdog. These sPATs would generally be too large for smaller fish. A new micro-PAT tag which weighs 46 g in air would facilitate tagging of spurdog ~ > 63 cm, but these tags are more expensive than the standard sPAT. The objectives behind additional tagging programs would need to be carefully defined in the context of ongoing assessment of potential new management measures.

Other tagging methods such as data storage tags and acoustic tracking are not considered suitable for survival studies due to the need to recover tags and/or non-detection of tagged individuals (Pollock et al., 2001; Morfin et al., 2019). Captive monitoring may be logistically challenging but would facilitate larger sample sizes and potential

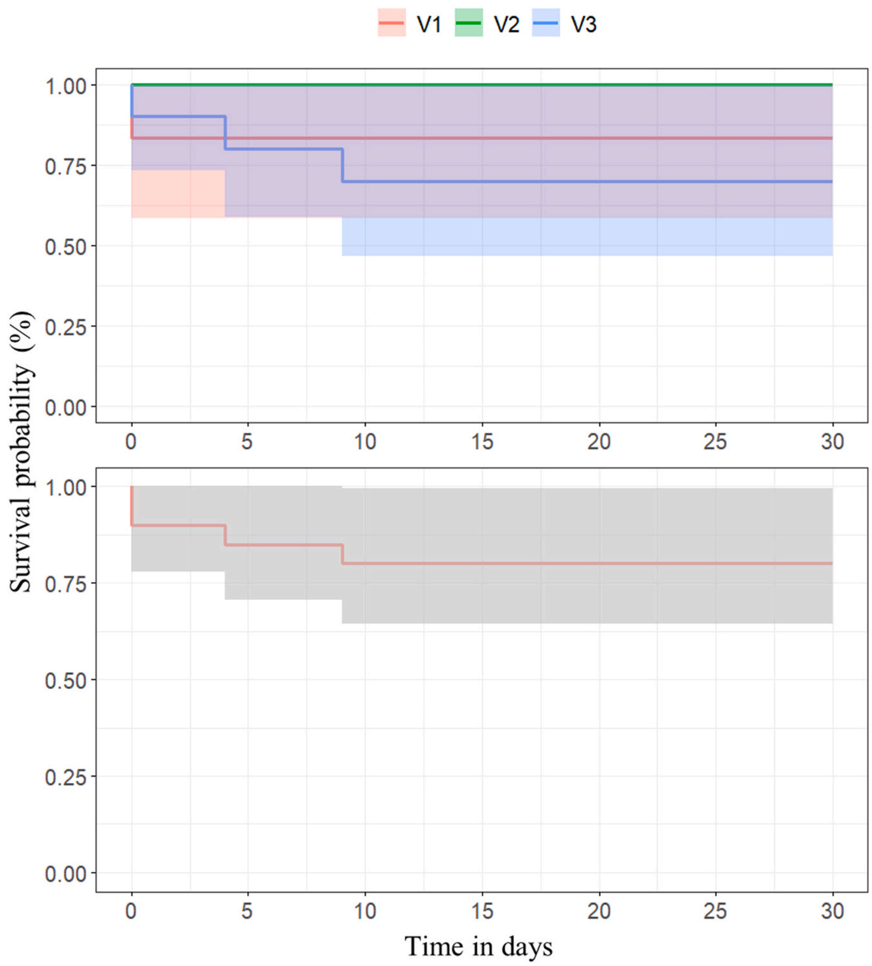

Fig. 4. (Top) Kaplan-Meier estimator for tagged spurdog consisting of six fish in excellent (V1), four fish in good (V2) and ten fish in poor (V3) condition with 95 % CI in shaded areas, (Bottom) Overall Kaplan-Meier estimator for 20 tagged spurdog with 95 % CI in shaded areas.

survival assessment of fish $\leq$ 63 cm.

The KM estimator demonstrated 80 % survival probability after 30 days for the 20 tagged spurdog. No mortalities occurred after day nine suggesting asymptote was reached by day 10 (Fig. 4). Breen and Catchpole (2021) note that reaching asymptote is important because it provides an endpoint for fish mortality and greater confidence that most of the mortality associated with catch and release is observed.

The overall survival estimate of 78 % for 80–100 cm is considered conservative due to our categorisation of non-reporting tags and spurdog in V4 condition as mortalities. Feedback from the tag supplier on possible explanations for the two non-reporting tags includes predation events, damage to tags or premature pop-up and beaching onshore which would prevent data transmission. Whatever the reason, we cannot rule out the possibility that either of these fish survived. Likewise, some of the V4 fish may have survived, particularly given the 70 % survival result for fish in V3 condition.

SPATs were effective in determining mortalities, but also in assessing fish behaviour during full-term deployments prior to finalising survival estimates and tag performance. Typical spurdog DVM (Carlson et al., 2014; Klöcker et al., 2024) was observed for all 17 survivors suggesting that normal behaviour resumed post release. Abnormal behaviour was observed in the case of Fish 20 which likely died soon after release and sank to the seabed where it remained for almost 4 days. The tidal range exceeded the 2 m depth variance threshold over this period which prevented tag pop-up. Hypothetically, this could have happened towards the end of a 30-day deployment period potentially resulting in a spurious survival result. However, the ability to interpret fish behaviour from the sPAT depth data would prevent this.

Gaps in the tag depth data occurred e.g. Tag 6 where some data were missing at the end of the deployment period. According to the tag manufacturer, data transmissions may have prematurely ended due to reasons such as beaching or getting tangled in seaweed or debris. The reasons for data gaps during the course of tag deployments, e.g. Fish 4 and 16, are unknown but this does not detract from survival results as normal behaviour was generally observed.

A variety of factors are likely to affect spurdog survival. Ellis et al. (2017) conducted a comprehensive review of post capture survival of elasmobranch species and found that survival varies in relation to biological attributes such as species, size, sex and mode of gill ventilation; fishery characteristics including gear type, soak time, catch mass and composition, handling practices, air exposure and changes in ambient temperature. In general, demersal species with buccal-pump ventilation survived better than obligate ram ventilators.

However, Ellis et al. (2017) found that elasmobranch species survival assessments are typically based on at-vessel or short-term post capture assessments which makes it difficult to directly compare outcomes with the current full-scale long-term assessment of spurdog survivability. Moyes et al. (2006) used PSATs to conduct a longer-term analysis on the survival of buccal-pump ventilating blue sharks caught using longlines and found that sharks landed in an apparently healthy condition are likely to survive long term if released. Differences in fish ventilation mechanisms and fishing gears precludes detailed comparison of results between the latter and current studies.

Spurdog is also caught off the west coast of Ireland using gill nets.

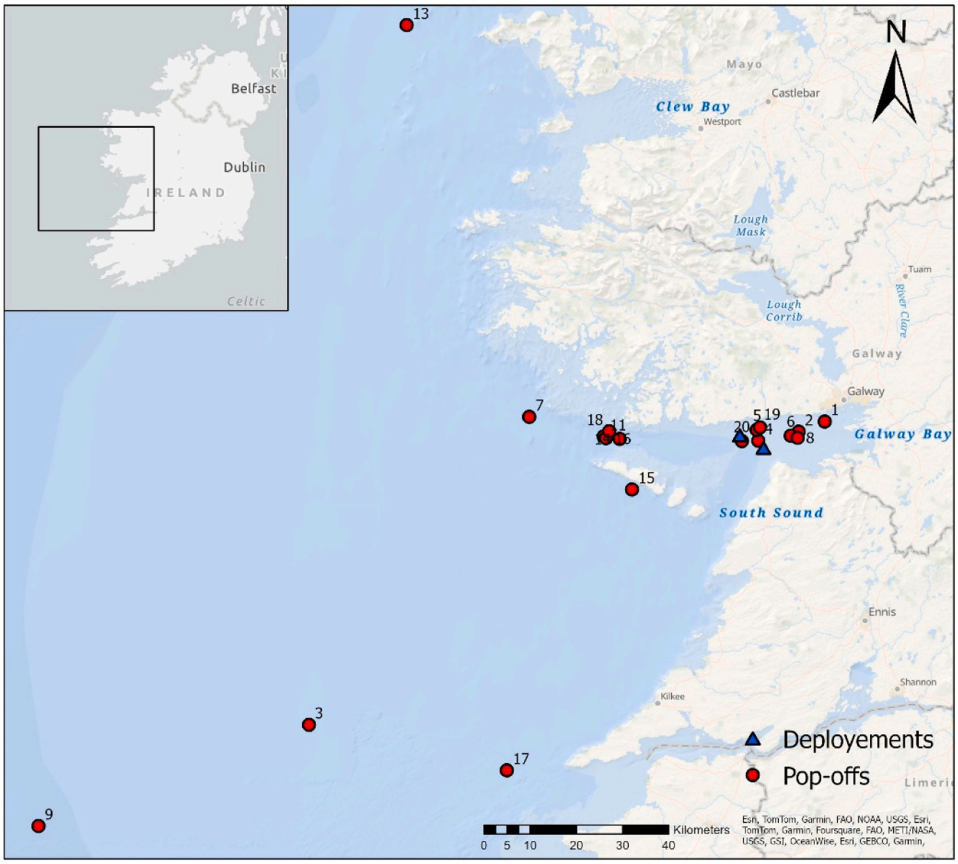

Fig. 5. PAT deployment and pop-up locations by Fish ID.

Table 9
Environmental data collected during tagging study.

Parameters	Oct-23	Mar-24	Jul-24
Mean sea surface temperature (°C)	15	11	17
Mean bottom temperature (°C)	14	9	13
Mean air temperature on vessel (°C)	14	11	18
Mean sea surface salinity (g/L)	30	35	35
Mean swell height (m)	1	1	1
Mean wind speed (knots)	20	12	24
Mean cloud cover (oktas)	6	2	4

Spurdog are likely subject to different stressors in gillnets compared with trawls. For example, they are generally static for longer periods which may affect their ability to ram-ventilate. On the other hand, they are not subject to the physiological stressors associated with lifting codends aboard. Full-scale assessment of spurdog survival in gillnet fisheries using the methods developed in the current study would help clarify these issues.

Ellis et al. (2017) describe how short-term survival of spurdog caught in trawl gears may be influenced by factors such as catch quantity, air exposure, handling practices and changes in temperature. Mandleman and Farrington (2007) demonstrated how catch weight in trawls affected spurdog survival likely due to increased physiological stressors from catch accumulation in the trawl codend. The largest observed spurdog catch during the current study was 550 fish during Haul 17 when seven fish were tagged. It took three lifts of the codend out of the water to take the catch aboard. Larger catches than this may occur but most of the stressors associated with catch weight are likely to occur when taking codend lifts aboard, regardless of the number of lifts. Of course, larger catches would also result in increased catch handling and air exposure times which could negatively affect fish condition and survival.

Air exposure times of up to 25 minutes occurred in the current study. Insufficient data precluded detailed analysis or inference on the effect of air exposure on spurdog survival. Any spurdog survival exemption would, however, need to be accompanied by efforts to minimise all forms of stress and injuries including air exposure and would benefit from the development of guidelines on best practice for handling spurdog. Recent research has demonstrated how survival assessment with pop up tags can inform such guidelines (Stewart et al., 2024).

Increased water temperature elevates stress levels in fish and can influence post catch and release survival (e.g., Gale et al., 2013; Kraak et al., 2018). In the current study, most spurdog were assessed during autumn and summer months when water and air temperature are at their highest. This bodes well for the survival of spurdog caught at other times of the year when temperatures are lower, and fish are likely to be in better condition when released. Due to logistical constraints, four spurdog (including two tagged spurdog) were assessed in March when temperatures were lower but this is unlikely to have had a major impact on study outcomes given the small number of fish involved.

DVM is often associated with foraging as sharks follow the daily migration of prey (Queiroz et al., 2012). Klöcker et al. (2024) noted that spurdog DVM was likely an indication of spatiotemporal alignment with local prey patterns and feeding activity. The authors also noted that variations between individuals and tagging years point to a complex interplay of movement behaviour and habitat use with the abiotic and biotic environment. In the current study, observed spurdog DVM in coastal areas and during transit to deeper more offshore waters is also likely indicative of foraging strategies. Longer-term tagging studies would be needed to more broadly understand spurdog behaviour off the Irish coast.

The European Commission, EU member states and the United Kingdom have commenced discussions with the International Council for the Exploration of the Sea (ICES) on new management measures for spurdog with the aim of optimising stock conservation and fisheries management. New information on spurdog survivability from the current study will greatly inform this process.

CRediT authorship contribution statement

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

Funding

This work was funded by the Irish Government and part-financed by the European Union through the European Maritime, Fisheries and Aquaculture Fund (EMFAF) Operational Programme 2021 – 2027.

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.

Acknowledgements

We would like to thank the skipper and crew of the MFV Karen Mary. Thanks also to Catherine Waters, Alan Drumm and Oliver Tully from the Marine Institute (Ireland) for collaboration around HPRA authorisation. We are also grateful to Devon Short and the staff at Wildlife Computers for technical support on the tagging.

Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.fishres.2025.107379.

Data availability

Data will be made available on request.

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