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Survivorship of discarded cuckoo ray in bottom trawl fisheries in the northern Bay of Biscay, Southern Celtic and Irish Seas

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Abstract :

Estimating the survivorship of discarded fish is often crucial for stock assessment and resultant management of fisheries resources. In order to assess the survivorship of cuckoo ray (Leucoraja naevus) caught in commercial bottom trawl fisheries, experiments involving French and Irish fisheries were conducted. These experiments were particularly challenging considering the fisheries are offshore. Data from these experiments were analysed jointly in this study. Results from monitoring of individuals held in captivity in onshore facilities and observations of vitality status were combined to produce estimates of long-term survival rates across fishing trips in all four seasons. These rates varied greatly between fishing trips and ranged between 3.6% and 26%. Based on indications that the observed mortality may be at least partly attributable to the conditions of captivity, we propose an approach to reduce the underestimation bias when estimating discard survival. This approach produced higher bounds for the estimated discard survival rates. The estimated survival rates are lower than those of other skate species in the North-East Atlantic, suggesting the cuckoo ray is less resilient to trawl-and-release, although previous studies were conducted in shallower water and with shorter haul duration.

Highlights

► The study combined vitality assessment in all seasons and monitoring in captivity. ► Estimated survivorship is poor compared to other skates in different fisheries. ► Survival rates varied markedly between fishing trips. ► A suggestion was presented to correct for mortality of controls in survival rates.

Keywords : Cuckoo ray (Leucoraja naevus), Discard survival, Captivity experiment, Bottom trawl fisheries, Vitality

1. INTRODUCTION

Estimating the survivability of fish discards and escapees has been a key component when quantifying and mitigating sources of unaccounted fishing mortality (e.g. Chopin and Arimoto, 1995; Davis, 2002; Gilman et al., 2013). Demonstrating post-capture survival in Europe has become more important since the introduction of the landing obligation (LO) in 2011 (Rihan et al., 2019). The landing obligation, introduced under the framework of the European Common Fisheries Policy (CFP), specifies that all species subject to Total Allowable Catch (TAC) or for which a minimum conservation reference size (MCRS) exists must be landed. Several exemptions to the landing obligation have been specified and Article 15, paragraph 2(b), of the CFP describes a survivability exemption applying to *"species for which scientific evidence demonstrates high survival rates, taking into account the characteristics of the gear, of the fishing practices and of the ecosystem"*. One key species group that has benefitted from a survivability exemption is the batoids (skates and rays).

Initial survival exemptions to the LO were granted for skates and rays using early assessments (Depestele et al., 2014; Enever et al., 2009; Kaiser and Spencer, 1995), provided that further work would be carried out to better inform discard survival. These exemptions were originally granted for three years, apart from cuckoo ray (*Leucoraja naevus*), which was granted a one-year provisional exemption in International Council for the Exploration of the Sea (ICES) subareas 6–9. This exception was justified based on observation of high immediate mortality, as well as an early assessment (Enever et al., 2009), and a data re-analysis (Catchpole et al., 2017; Ellis et al., 2012). The Catchpole et al. (2017) re-analysis estimated 34-35% long-term survival. However, more substantial data are needed to determine the survival rates for discarded cuckoo ray because of the short monitoring time (4 days) and small sample size (n=26) (Catchpole et al., 2017).

Cuckoo rays are distributed from Morocco and Senegal to the Shetland Isles in the Atlantic (Quéro and Vayne, 1997; Whitehead et al., 1984), and are also present in the Mediterranean Sea. The species occupies a wide depth range in the Celtic, North and Irish Seas, with individuals observed from 12 to 510 m with greater densities in the deeper areas (Ellis et al., 2005; Figueiredo et al., 2007), making this species mostly caught in offshore fisheries.

International Council for the Exploration of the Sea subareas 7 and 8 contributed 61% and 30% of cuckoo ray landings in the North-East Atlantic, respectively, with an annual mean of 2,784 tonnes landed between 2017 and 2021 (ICES, 2022). Bottom trawlers account for 89% of cuckoo ray landings. French and Irish vessels produced 83% and 2%, respectively, of cuckoo ray landings in subareas 7 and 8 over the 2017–2021 period. French landings of cuckoo ray by bottom trawlers mostly originate from an area encompassing the southern part of the Celtic Sea and the north of the Bay of Biscay (Source: Système d'Information Halieutique – SIH).

The cuckoo ray is primarily caught incidentally by French vessels targeting monkfish (*Lophius piscatorius* and *L. budegassa*), and to a lesser extent gadoids, while the major contribution to Irish landings is made by vessels targeting gadoids/whitefish (mainly *Melanogrammus aeglefinus*, *Merlangius merlangus*, *Gadus morhua*) or blonde ray (*Raja brachyura*). Typically, French vessels land larger sizes (> 60 cm, total length—TL) for market, while very few are landed by Irish vessels because of their low value. The 2022 assessment of the cuckoo ray stock considered here (cuckoo ray in west of Scotland, southern Celtic Seas, and western English Channel, Bay of Biscay) by ICES indicated a healthy biomass status with a fishing mortality below that producing the maximum sustainable yield (MSY) (ICES, 2022). The current assessment is based on landings only, as total discarded quantities and associated survival rates are unknown.

The aim of this study is to estimate long-term post-capture survival of discarded cuckoo ray caught by otter trawlers (single and twin-rigged bottom trawls) targeting demersal fish and operating in ICES subareas 7 and 8 during all four seasons, in circumstances representative of commercial practices in this area. The ICES Working Group on Methods for Estimating Discard Survival (WGMEDS) (ICES, 2020) and Scientific, Technical and Economic Committee for Fisheries of the European Commission (STECF) (STECF, 2014) have issued recommendations regarding experimental approaches to produce representative estimates of discard survival rates. To meet these requirements, it is advised to perform vitality assessments onboard commercial vessels during a representative range of conditions, and combine this with tagging and/or monitoring through biotelemetry of released individuals (with vitality assessments) or observation of the fate of the individuals held in captivity. The monitoring of individuals for an extended period of time after capture is necessary to estimate delayed mortality, which may occur for several weeks after release. For cuckoo ray, the depth and spatial extent of the habitat in the area of interest preclude the tagging of individuals released at sea. For this reason, captive monitoring in onshore holding facilities was deemed the best fit for the current study which, to the best of our knowledge, is the first to provide estimates of discard survival rates for cuckoo ray caught in offshore waters.

In both the Irish and French experiments, cuckoo rays caught during commercial fishing trips were held in shore-based holding facilities and monitored for several weeks. We analyzed the data collected from these experiments to estimate the long-term discard survival of cuckoo ray in conditions representative of commercial activities, from various vessels and seasons.

1. MATERIAL AND METHODS

The post-capture survivorship of cuckoo ray discarded by bottom trawlers in the North-East Atlantic was analyzed over four seasons based on experiments in captivity, with similar but not identical protocols.

Two different types of trips involving commercial fishing vessels were performed in the French experiments: trips to collect cuckoo ray for subsequent survival monitoring in captivity and trips to estimate the distribution of a vitality score among the discarded individuals (distribution of sampling stations in Supplementary Figure S1). The French captivity experiments were carried out over two seasons (winter and summer) following a sampling stratified by fish vitality, while the distribution of the vitality score over larger samples was established in spring (2019), summer (2020) and winter (2020–2021). In the Irish experiment, the same fishing trips were used for the two purposes. These trips were conducted in autumn 2021. Data from both Irish and French experiments were combined into a common analysis.

1.1. Representativeness of the experiments

The representativeness of the vessels and fishing operations sampled during the different experiments was assessed by comparing their features to those of the vessels and fishing operations in the corresponding fleets, as sampled by the respective national onboard observation programs. The experiments carried out on French vessels focused on a fleet of bottom otter trawlers (single or twin-rigged) operating in a larger area (ICES divisions 8a and 7h,j) and targeting demersal fish, with frequent by-catch of cuckoo ray. Within this fleet, the sampled vessels were fishing with twin-rigged otter trawls, using a codend with 100-mm diamond meshes (stretched). For the Irish experiment, the relatively low frequency of cuckoo ray catches by the fleet targeting gadoids/whitefish hampered their collection. To circumvent this issue, an otter trawler (Vessel 5) with similar characteristics and using the same gear (single-rigged otter trawl) as those operating in the Irish Sea was used to collect cuckoo rays. This vessel equipped with a 120-mm diamond-mesh codend, operates in ICES Division 7a and targets skates (mostly blonde ray *Raja brachyura*), which generates cuckoo ray bycatch.

When comparing the vessels used and conditions encountered for the experiments with data from the national onboard observation programs, only observed fishing trips associated with cuckoo ray discarding were considered. In order to reduce the variability generated by small sample sizes, data from the French national onboard observation program collected from 2017 to 2021 were pooled. To describe the environmental conditions encountered during the different fishing operations, logs from the closest meteorological buoys for the corresponding days were used. The two buoys used for the Irish and French experiments are the M2 Weather Buoy (located at 53.4836° N, -5.4302° W) and Buoy 62163 (located at 47.5500° N, 8.4700° W), respectively. These records were compared to values of the various parameters recorded over the same seasons from the same buoys, calculated over the period 2019–2021. In addition to being characterized by weather conditions, fishing operations were described by fishing depth, tow duration and bulk catch weight.

Cuckoo rays assessed for post-capture survival were collected with standard gears used by the fleets of interest (twin- and single-rigged otter trawls for French and Irish fleets, respectively), without any selective devices other than the ones legislated for (see Regulation (EU) 2019/1241). The trawlers on which sampling occurred did not modify their fishing practices and frequented their usual fishing grounds during the experiment.

1.1. Vitality assessment

Vitality status was assessed for all individuals according to a semi-quantitative assessment (SQA) score. The SQA applied here was based on four ordinal vitality categories defined by Benoît et al. (2010) (Table 1). Vitality assessment was performed quickly, typically within a few seconds (maximum 5 seconds). Within SQA category D (Moribund), the determination of dead individuals was done by repeating the gentle tapping behind one eye and if no eye or spiracle movement were noticeable, the cuckoo ray were declared dead. Details on the collection of individuals are provided in Supplementary Material.

Table 1. Description of the different categories of the semi-quantitative vitality assessment (SQA) score, based on Benoît et al. (2010).

State	Category	Description
Excellent	A	**Vigorous body movement**; no or minor external injuries only
Good	B	**Weak body movement;** responds to touching/prodding; minor external injuries
Poor	C	**No body movement** but can move spiracle opening; minor or major external injuries
Moribund	D	**No movement of body or spiracle opening** (no response to touching or prodding)

1.2. Sampling and captivity

In the autumn experiment, vitality assessment and monitoring of survival in captivity were performed on the same individuals. The distributions of vitality categories observed during this experiment were considered representative of discards from the focus fleet. The sanitary restrictions in place during the COVID-19 pandemic prevented the presence of scientific observers onboard Vessel 5 at the time the experiment was conducted. Therefore, vitality assessments were made upon arrival at port, before the fish were transferred to onshore holding facilities located on the pier to limit transport-induced stress.

For the French experiments, sampling involved two components, with some trips dedicated to the collection of individuals later held in captivity ('captivity trips') while others were dedicated to the assessment of vitality on a larger and therefore more representative number of fish ('vitality trips', Table 3 and Supplementary Table S2). A single vessel (Vessel 2) was used for the captivity trips and a total of four vessels were used for the French experiments, with scientific observers present (one observer during 'vitality trips' and two during 'captivity trips'). Therefore, individual vitality was sampled onboard, during catch sorting by the crew.

The SQA was used to define strata for the sampling design in 'captivity trips', with the objective of monitoring identical numbers of individuals within each category A to D.

The number of dead individuals by fishing operation, used to derive the immediate mortality rate, was also reported. Any mortalities at sea were recorded for inclusion in the overall survival estimate. Live individuals collected during the Irish experiment were transferred into three onboard tanks whereas those collected during French 'captivity trips' were transferred into individual boxes (holding conditions detailed in Supplementary Material).

In all experiments, individuals were placed into the tanks or boxes during catch sorting. These individuals whose post-capture survival is to be estimated are termed 'test' individuals. They are distinct from 'control' individuals, separately collected to assess the impact of holding conditions on survivorship.

Once ashore, cuckoo ray collected during the Irish experiment and French 'captivity trips' and that were still alive were transferred into larger tanks lined with sand (except for the winter experiment). For the Irish experiment, individuals were tagged using colored hook and loop straps around the tail for identification purposes while a nylon T-tag with a serial number was attached to the first dorsal fin in the French experiments. The tagging methods employed here resulted in no or very minor lesions on the individuals.

Cuckoo ray were monitored during captivity and checked from twice (French experiments) to four times a day (Irish experiment), and dead individuals were removed from the tanks.
As for the 'vitality trips' in the French experiments, four trawlers were sampled between April 2019 and February 2021, with two vessels sampled per season (Table 3). Vessels 1, 3 and 4 were used for the vitality trips in spring, winter and summer experiments, respectively, while vessel 2 was used for all the seasons. The same scientific observer recorded vitality on a sample of cuckoo ray intended to be discarded, during each fishing operation. An upper limit of 30 sampled individuals per fishing operation was set during these 'vitality trips', so that the total time necessary to observe vitality of half the sampled individuals did not exceed the time required to sort the catch and discard the unwanted fish.

In the French experiments, data from 'vitality trips' conducted in winter and summer were naturally associated with the results of the captivity experiments conducted in the same seasons. However, as no 'captivity trips' were conducted in spring, it was decided to associate data from the spring 'vitality' trips with the results of the captivity experiment presenting a greater similarity with conditions observed in spring and presenting a high control survival rate(i.e. a low survival rate of controls is associated with a lower reliability of survival estimates).

After consultation of internal (Ifremer, France) and national (Health Products Regulatory Authority, Ireland) authorities regulating animal experimentation regarding the protocols applied, it was concluded that these experiments fell outside the scope of the legislation and therefore no specific authorizations were required. It was nevertheless ensured that all the procedures applied for this study followed the recommendations established by Directive 2010/63/EU of the European Parliament and of the Council of 22 September 2010 on the protection of animals used for scientific purposes.

1.3. Control individuals

Control individuals were collected to evaluate the mortality induced by the onboard and onshore holding conditions. They were caught during the same fishing trips but from shorter hauls, to reduce traumas associated with the capture process. Unlike other ('test') individuals, they were directly transferred into tanks or individual boxes, before the whole catch was sorted.

In the Irish experiment, control individuals were collected during short hauls of 50 to 60 minutes. Because the vitality status of the 12 individuals collected during shortened hauls is unknown at their arrival upon the vessel's deck, only individuals in SQA classes A and B were finally considered control individuals (8 individuals). One of the individuals used as controls was collected from a short haul some days before the experiment to ensure onshore holding facilities were suitable.

In the French experiments, the collection of control individuals during 'captivity trips' took place at the beginning of each two-day trip during short hauls (duration: 22 min to 1 h 8 min) (Supplementary Table S1). Technical improvements were made for the summer experiment compared to the winter experiment—a tarpaulin-covered cod-end was employed. This adjustment allowed fish to be kept in the water until the cod-end was retrieved. It also reduced abrasion resulting from the trawl’s netting. Only individuals of less than 60 cm in body length and displaying excellent vitality (SQA class A) were used as controls.

2.2 Survival assessment

2.2.1. Survival model

The approach proposed by Benoît et al. (2012) and recommended by WGMEDS was adopted here to estimate the long-term survival rate of discarded cuckoo ray.

For fish that survived the duration of the experiment, the data were right-censored since the captivity experiments were halted before the death of all test individuals. Because many deaths occurred among controls, monitoring periods were set, corresponding to a minimum of five controls still alive in tanks. Below this minimum number of individuals, it was considered that the mortality related to captivity could not be reliably assessed. The restricted observation periods corresponded to 15, 18, and 26 days for the autumn, winter, and summer experiments respectively.

Cure rate models were fitted to the data from the different experiments to describe both survival time and the probability to survive from the fishing operation (Benoît et al., 2015; Farewell, 1982). The survival probability S defined as a function of time t and a covariate or set of covariates ϑ can be expressed as

$$S(t, \vartheta) = 1 - \pi(\vartheta) + \pi(\vartheta)\, F(t, \vartheta),$$

where $\pi(\vartheta)$ is the delayed mortality rate or asymptotic mortality modelled as a Bernoulli process and $F(t, \vartheta)$ represents the probability of surviving until time t for individuals subsequently dying. t=0 corresponds here to the introduction of individuals into the onshore tanks for the autumn experiment while it corresponds to the time of onboard vitality assessment for the winter and summer experiments. The calculation of $S(t, \vartheta)$ accounts for right-censoring.

Two statistical distributions of the survival times (described by $F(t, \vartheta)$) were tested: Weibull and exponential. For a particular set of covariates, the models can be written as

$$S(t)=1-\pi + \pi \exp\left(-(\alpha\, t)^{\gamma}\right),$$

with the particular case γ=1 corresponding to the exponential distribution. Parameter α acts upon the slope of the survival curve.

2.2.2. Vitality-dependent survival

The relationship between vitality and discard survival was established for all captivity experiments by introducing the influence of the SQA score on parameter π, based on the following relationship:

$logit(\pi_i)=a_{\pi,j(i)}$

where *i* indexes the individual and *j* indexes SQA category. To account for potentially different shapes of the curve describing the survival times of individuals that did not survive, we also tested models including vitality as a predictor of parameters α and γ, based on the following relationships:

$ln(\alpha_i)=a_{\alpha,j(i)}$

$ln(\gamma_i)=a_{\gamma,j(i)}$

Model parameters were estimated based on the maximum likelihood with the optim function from the "stats" library in R (R Core Team, 2021), with constrained optimization based on the "L-BFGS-B" algorithm. The best model, used for deriving the final survival rates, was selected based on the Akaike information criterion (AIC).

The distributions of two types of residuals were examined: Cox-Snell (Scolas et al., 2018) and Normalised Random Survival Probability (NRSP) residuals (Li et al., 2021). The agreement of the Cox-Snell residuals with the expected distribution of residuals according to the selected (i.e. Weibull or exponential) probability density function was visually assessed, and Shapiro-Wilk tests of normality were performed on NRSP residuals.

The 95% confidence intervals associated with the final estimates of cure rates π were estimated based on bootstrapping (n=500) of the observed individuals. Model convergence time was defined as the necessary time for most of the discarding-related mortality to occur, here corresponding to the time for the estimated survival rate to fall below $1 - 0.99\pi$.

As in mixture cure models the survival function $F(t, \theta)$ must respect the condition$F(0, \theta) = F(t, \theta) = 1$, immediate mortality (occurring before the vitality assessment) could not be directly incorporated into the models. Therefore, we considered immediate mortality rate as a distinct process estimated independently from the survival model. The estimates of final survival rates of the discarded cuckoo rays per fishing trip were obtained by multiplying the delayed survival rates obtained in captivity by either:

- the proportion of fish alive at the time of the vitality assessment (Irish experiment)
- the proportion of fish alive during the 'vitality' trips (French experiments)

3. RESULTS

The 72 individuals collected for the autumn survival assessment were caught during four consecutive fishing trips (14 hauls) completed in September and October 2021 (Table 2 and Supplementary Table S1).

A total of 172 individuals were collected during the French captivity trips, 143 of which were test individuals (Table 2, Supplementary Table S1).

Table 2. Summary of the collection of individuals in the Irish and French experiments.

Season	Vessel	Dates of fishing trips	No of Test (control) hauls	No of test individuals	No of control individuals
Autumn	5	20/09/2021 to 22/09/2021	5 (1)	17	1
		28/09/2021 to 29/09/2021	5 (1)	34	10
		05/10/2021	1	5	0
		09/10/2021	1	5	0
Winter	2	29/02/20–01/03/20	2(1)	24	4
		02/03/20–04/03/20	2(1)	24	5
		04/03/20–05/03/20	2(1)	23	5
Summer	2	30/08/20–31/08/20	2(1)	24	5
		31/08/20–02/09/20	3(1)	24	5
		04/09/20–05/09/20	2(1)	24	5

Table 3. Summary of 'vitality' fishing trips in the French experiments.

Season	Vessel	Dates of fishing trips	No of Hauls	No of observed individuals
Spring	Vessel 2	10/04/2019 to 23/04/2019	33	552
	Vessel 1	01/05/2019 to 08/05/2019	17	316
Winter	Vessel 2	17/01/2020 to 29/01/2020	19	222
	Vessel 4		17	129

		16/12/2020 to 21/12/2020 and 03/02/2021 to 15/02/2021	40	159
Summer	Vessel 2	01/08/2020 to 12/08/2020	13	157
	Vessel 3	13/07/2020 to 20/07/2020	24	185

3.2. Sampling representativeness

The characteristics of the vessels sampled for these experiments fell within the range in the corresponding fleets (Tables 4 and 5), despite the sampled vessels being slightly larger and with greater engine power than the average. Similarly, duration and depth of the fishing operations during sampled trips reflected features of the focus fleets. In addition, the sampled fishing operations were conducted in meteorological conditions representative of conditions experienced during the different observation periods. The Irish experiment involved the collection of 46 females and 15 males. Total body length of test individuals ranged between 27 cm and 61 cm, with a mean of 41.6 cm (s.d. = 8.9 cm). Mean body length did not significantly differ between control and test individuals (two-sided Student's T-test, t =- -1.190, df = 8.505, p = 0.266).

Table 4. Characteristics of fishing operations during the Irish experiment. Ranges are between parentheses.

Characteristics	Mean (range) during the experiment	Mean (range) for the fleet
Vessel length	22.0 m	16.8 m (10.05–38 m)
Vessel power	442 kW	234 kW (20–1119 kW)
Haul duration	3h44' (2h15'–5h00')	4h (2h00' – 5h00')
Fishing depth	112 m (64–146 m)	100 m (30 – 150 m)
Catch weight	293 kg (168–553 kg)	NA
Wave height	0.96 m(0.0–2.0 m)	1.02 m (0.15–2.18 m)
Air temperature	15.1°C (14.0–17.0°C)	14.3°C (11.2–17.5°C)
Duration of air exposure	0h12'30'' (0h10'–0h20')	NA
Total length of fish	41.6 cm (27–61 cm)	NA

Table 5. Characteristics of fishing operations during the 'vitality' fishing trips (French experiments). Ranges are presented between parentheses.

Characteristics	Season	Mean (range) during the vitality experiment	Mean (range) for the fleet or season
Vessel length		22.7 m (20.4–24.9 m)	20.5 m (10.4–38.0 m)
Vessel power		471 kW (385–600 kW)	405 kW (129–884 kW)
Haul duration	Winter	4h42’ (2h40’–6h30’)	4h47' (0h45'–7h20')
	Spring	5h01’ (3h00’–6h10’)	4h51' (1h47'–6h45')
	Summer	4h45’ (3h30’–7h45’)	4h36' (2h30'–6h40')
Fishing depth	Winter	147 m (120–300 m)	147 m (25–280 m)
	Spring	165 m (120–290 m)	151 m (74–320 m)
	Summer	172 m (120–440 m)	136 m (74–260 m)
Catch weight	Winter	402 kg (150–1100 kg)	500 kg (167–2048 kg)
	Spring	544 kg (250–1100 kg)	513 kg (139–1350 kg)
	Summer	460 kg (250–1200 kg)	378 kg (53–972 kg)
Wave height	Winter	3.7 m (1.7–6.3 m)	3.7 m (0.7–12.3 m)
	Spring	2.1 m (1.3–3.6 m)	2.1 m (0.5–7.6 m)
	Summer	1.5 m (1.1–1.9 m)	1.9 m (0.5–8.1 m)
Air temperature	Winter	11.2°C (8.5–13.9°C)	11.2°C (6.3–13.9°C)
	Spring	12.4°C (11.1–13.5°C)	13.2°C (6.2–17.7°C)
	Summer	17.2°C (15.5–18.7°C)	17.4°C (12.7–20.4°C)
Duration of air exposure	Winter	0h30’ (0h12’–0h54’)	NA
	Spring	0h36’ (0h15’–1h53’)	NA
	Summer	0h33’ (0h12’–1h03’)	NA
TL	Winter	40.6 cm (15–64 cm)	41.6 cm (13–72 cm)

Spring	39.7 cm (12–68 cm)	38.7 cm (12–66 cm)
Summer	38.9 cm (18–56 cm)	34.3 cm (10–61 cm)

Beside seasonal effects, a pronounced variability between individual vessel practices emerged. For example, deep trawling was observed for Vessel 2 in the summer, but this corresponded to limited amounts of cuckoo ray (17 individuals caught below 300 m, representing 11% of all individuals sampled during the trip). The duration of air exposure was relatively constant among seasons and vessels, with one exception (unusually long catch processing due to damage to the gear, in the spring) (Table 5).

The individuals collected during the 'captivity trips' in the French experiments were between 20 and 57 cm TL (n = 143, mean = 38.6 cm, sd = 7.7 cm). Their mean length did not significantly differ from that of individuals collected during the 'vitality trips' (two-sided Student's T-test, $t = 1.939$, $df = 183.05$, $p = 0.054$). In addition no significant difference appeared between the lengths of test and control rays (two-sided Student's T-test, $t = -0.328$, $df = 32.717$, $p = 0.745$).

Vessel 2 tends to stand out among the focus fleet based on its longer hauls during the 'vitality trips' (average of 5h30min versus 4h22min for the other observed vessels within the target fleet) (Supplementary Figure S6). It also frequented deeper fishing grounds than most other French bottom trawlers targeting demersal fish in subareas 7 and 8 (average of 230 m versus 127 m for the other observed vessels within the focus fleet). The singularity of practices of Vessel 2 did not reflect during 'captivity trips'.

3.3. Vitality

In the Irish experiment, twenty-two mortalities occurred while at sea and during transit and were treated as mortalities at time zero (corresponding to immediate mortality rate of 29.5%). Consequently, a total of 39 test cuckoo rays were retained for captive observation. The distribution of SQA categories was dominated by individuals in excellent condition or moribund, with an equal contribution of 41% of observed cuckoo ray (Figure 1). SQA categories B and C represented 8.2% and 9.8% of the sampled individuals, respectively.

Vitality assessment was performed on 1720 individuals over three seasons in the French experiment (Table 3). Unlike for the autumn experiment, individuals observed in SQA category A never predominated in the distribution of SQA for the French experiments (Figure 1, Supplementary Table S2). Instead, the distribution of SQA categories was dominated by individuals of good (category B, in the summer) or poor (category C, in the spring and winter) vitality (Figure 1). Besides varying between seasons, the distribution of SQA categories fluctuated between vessels within a given season for the French experiments (Supplementary Table S2), and so did immediate mortality rates. Immediate mortality showed a rather high variability, with values varying from 2.5% (in the spring, for Vessel 1) to as high as 28% (in the summer, for Vessel 2). The SQA results provided a similar signal, the spring trip performed by Vessel 1 was associated with the least impacted cuckoo rays. Conversely, within a single season, individuals observed aboard Vessel 2 almost systematically presented a lower vitality than on the other vessels.

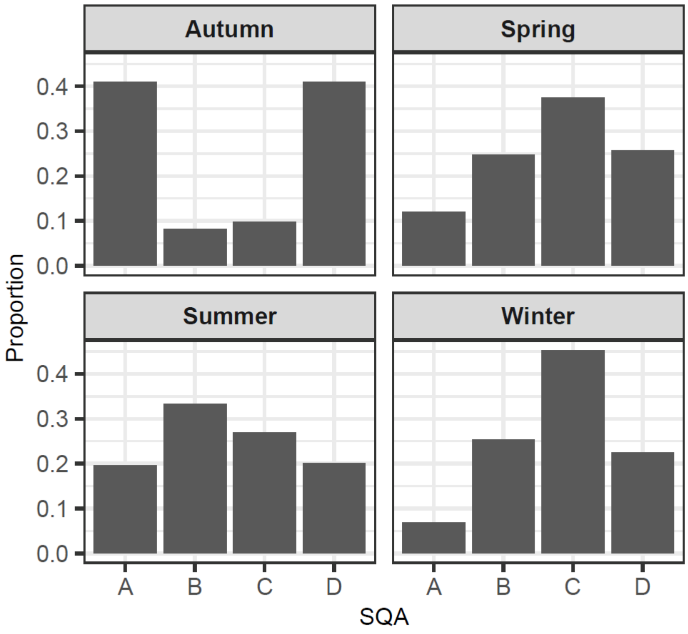

Figure 1. Distribution of proportions of individuals by SQA class for each season, in 'vitality trips'.

3.4. Model selection

Regarding the selection of mixture models describing the survival of cuckoo ray, models associated with the lowest AIC values were based on a Weibull distribution of survival times in all cases (Supplementary Table S3). In addition, a common parameterization was selected according to the same criterion. The best models for the winter, summer and autumn experiments therefore all have parameters α and π dependent on the SQA score, while the shape parameter γ is fixed within each experiment. This parameterization was used to derive the estimates of final survival rates.

The graphical examination of Cox-Snell and normalised random survival probability residuals suggests some departures from normality (Figure 2), particularly for the summer experiment. This is confirmed by p-values consistently lower than 0.05 associated with Shapiro-Wilk normality tests on the distribution of NRSP residuals (not shown). The examination of Cox-Snell residuals suggests that these violations are mostly generated by the fit of the survival curves to individuals within SQA categories C and D. Based upon the visual assessment of the distribution of residuals, which did not show pronounced skewness, we deemed that the potential estimation bias was expected to be limited. We therefore used the outputs of the selected models despite the existing deviations of the two types of residuals from normality.

3.5. Survival in captivity

In most cases, the convergence of the survival curves is observed during the observation period, as illustrated by a convergence time usually shorter than 3 weeks (Table 6). A notable exception is observed for SQA category B in the summer experiment, with a convergence time estimated at 85 days. However, no mortality having been observed passed day 11 (Figure 3), the corresponding estimate of asymptotic survival rate was assumed reliable.

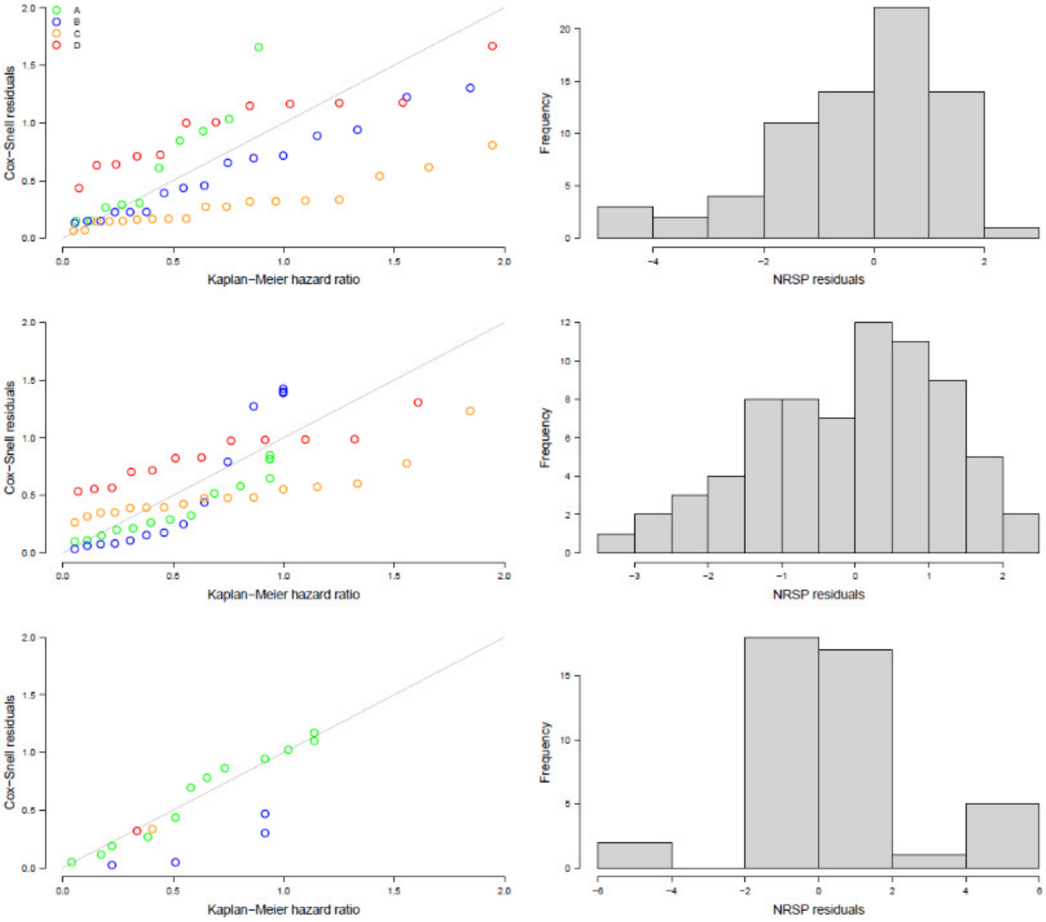

Figure 2. Cox-Snell and normalized random survival probability residuals from survival models based on the SQA for each experiment. From top to bottom: winter, summer, autumn experiment.

Table 6. Results of the survival models fitted by SQA category for each experiment. Asymptotic survival rate, with lower and upper bounds of 95% confidence interval (CI) and convergence time.

Experiment	SQA	Asympt. Surv. (%)	Lower CI	Upper CI	Conv. time (days)
Autumn	A	28.4	0.0	50.3	19.0
	B	40.3	0.0	87.4	16.0
	C	0.2	0.0	11.1	2.0
	D	0.0	0.0	8.6	2.0
Summer	A	42.8	0.1	64.3	19.0
	B	29.6	0.0	59.7	85.0
	C	6.9	0.0	28.7	9.0
	D	6.9	0.0	26.8	5.0
Winter	A	18.7	0.0	43.6	31.0
	B	7.8	0.0	30.5	10.0
	C	0.1	0.0	2.2	6.0
	D	8.1	0.0	26.5	3.0

As expected, individuals originally in SQA categories A and B experienced higher survival than individuals classified as C or D, with survival rates decreasing at a slower pace and reaching higher asymptotic values. For a given SQA category, the estimated asymptotic survival rates vary substantially across experiments. Higher absolute variations are observed for categories A and B. Asymptotic survival rates vary from 18.7% in the winter to 42.8% in the summer for category A, and from 7.8% in the winter to 40.3% in the autumn for category B. Less variation is associated with estimates of asymptotic survival for SQA categories C and D, which are always low values (<10%). The extent of the confidence intervals around these estimated asymptotic survival rates depends on the experiment as well as the SQA category. They tend to be narrower in the summer and they span a wider range of values for SQA categories C and D. The estimated lower bound of the 95% confidence interval is always very close to zero.

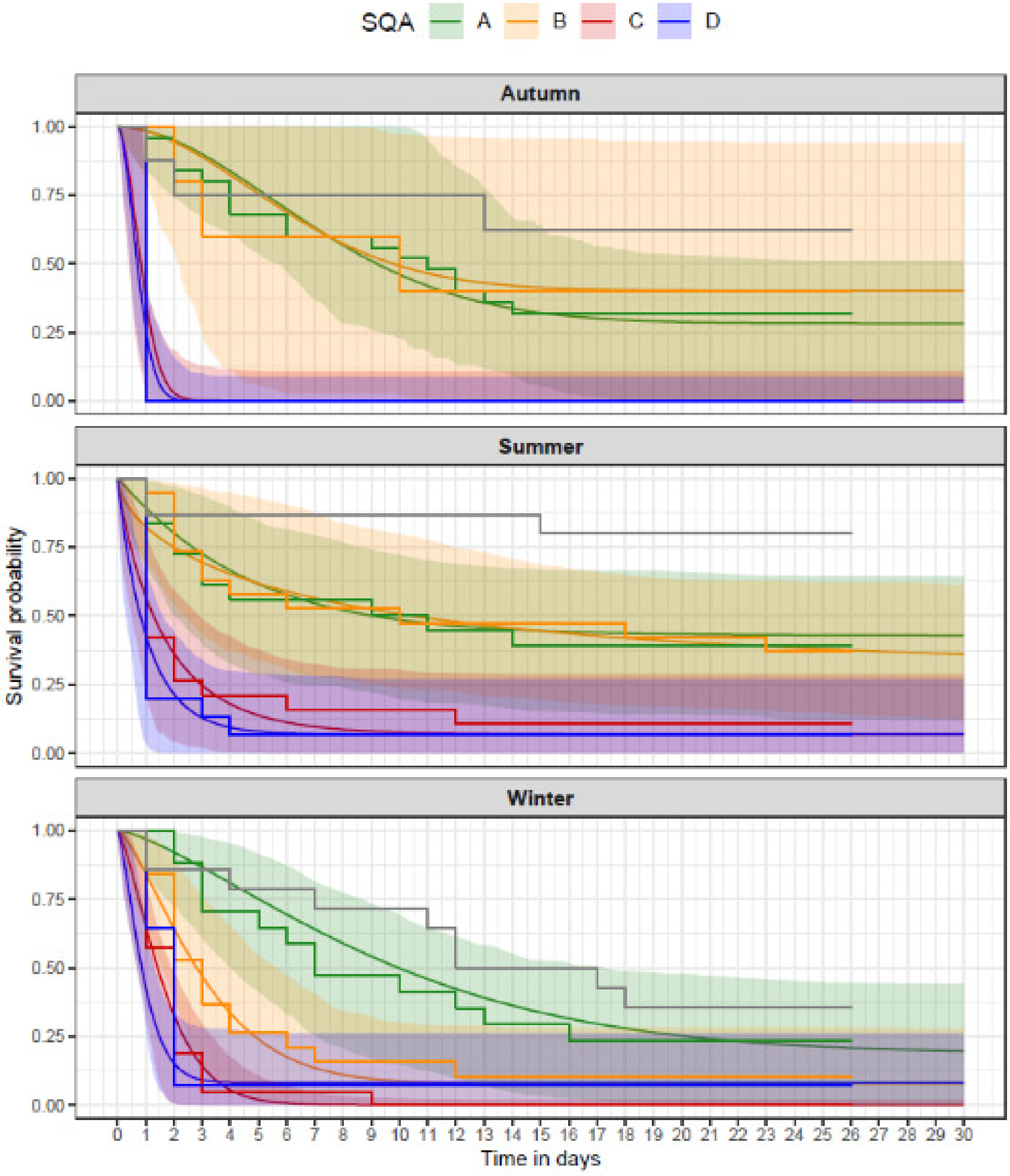

Figure 3. Kaplan-Meier survival curves (curves by parts) and model fits (continuous curves) for cuckoo ray kept in captivity, with 95% confidence intervals around model predictions as shaded areas, for each SQA category, by season. The grey curves represent control individuals.

3.6. Exploration of a potential linkage between mortality of controls and mortality of test individuals

A variable fraction of the control individuals did not survive throughout the entire observation period, depending on the experiment. At the end of the monitoring period (earlier defined as 15, 26 and 18 days for autumn, summer and winter respectively), the survival rates of controls were 62.5%, 80% and 35.2%for the autumn, summer and winter experiment, respectively. Whereas the survival curves of controls corresponding to the summer and autumn experiments displayed an initial abrupt decrease in the proportion of surviving individuals before a relative stabilization of the survival rate, the survival rate observed during the winter experiment did not level off before the end of the observation period (Figure 3).

When considering the estimated delayed survival of test individuals in relation to the survival of controls, a pattern of positive association seems to emerge (Figure 4, left), with higher survival of test individuals in a given SQA category observed in situations of higher survival of controls. This positive association appears more pronounced for SQA categories A and B. More specifically, the plot of ratios of survival of test individuals versus survival of controls (Figure 4, right) suggests a constant ratio for each SQA category. Such a proportional relationship would be expected in a situation where holding conditions would similarly affect the survival of test and control individuals. This situation would justify the application of a correction factor to compensate for the associated underestimation of survival rates.

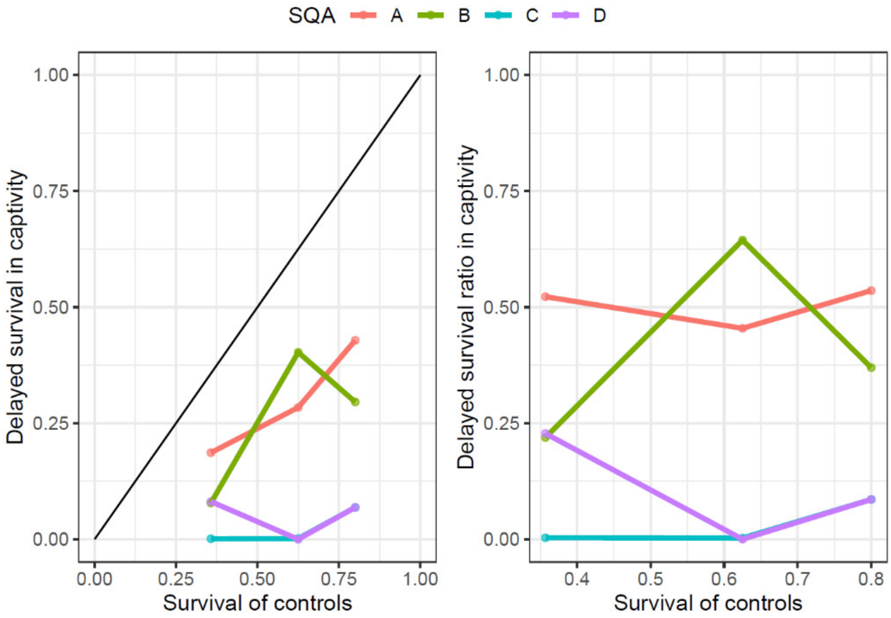

Figure 4. Delayed survival rate (left) and ratio (right) in relation to survival of controls in captivity

3.7. Discard survival in commercial fishing conditions

Discard survival was estimated per trip, from the combination of immediate mortality, asymptotic survival rate by SQA category and the distribution of individuals between these vitality categories.

Due to the low survival rates of control individuals in the winter experiment, the survival rates estimated for test individuals in the summer experiment were used to derive the overall survival of discards in the spring fishing trips. Indeed, the uncertainties around estimating survival rates and their interpretation increase with the mortality of control individuals. When no correction for mortality in controls was attempted, the estimated final survival rates per fishing trip varied between 3% (winter) and 23% (spring) (Table 7). For the French experiments, the lower values are associated with Vessel 2 within every season.

Table 7. Final estimates of survival rates, corrected and uncorrected, by fishing trip based on vitality assessment, immediate survival, and associated survival rates of controls (*Surv.*: uncorrected, *Corr. Surv.*: corrected using the survival rate of controls *Surv. Ctrl*).

Season	Vessel	Surv. Ctrl	Surv.	Corr. Surv
Autumn	5	62.5%	16.5%	26.4%
Spring	2	80.0%	11.8%	14.7%
Spring	1	80.0%	22.9%	28.6%
Summer	2	80.0%	13.9%	17.4%
Summer	4	80.0%	26.0%	32.5%
Winter	2	35.7%	3.6%	10.1%
Winter	3	35.7%	4.6%	13.0%

Under the joint hypotheses that total mortality of controls is imputable to holding conditions only and that the adverse effect of captivity on survival is multiplicative and affects individuals in all vitality classes in a similar way, a multiplicative correction factor can be applied to the final survival rates. It is equal to the inverse of the control survival rate in the associated captivity experiment. Applying this correction increases the survival rates per trip to between 10.1 and 32.5% (Table 7). The consequence is more pronounced for winter trips, with a 280% increase in the survival rate.

Accounting for this correction only marginally modifies the relative survival between seasons, with the lower values still estimated for winter trips.

4. DISCUSSION

This study offers a valuable insight into the variability of discard survival of cuckoo ray by otter trawlers targeting groundfish in the North-East Atlantic for a wide range of environmental, technical and biological conditions. The sampled fishing trips cover most of the range of conditions encountered in the areas considered and are representative of trips conducted by the focus fleets. In both Irish and French experiments, the sampled vessels are slightly larger and have a greater engine power than the average vessel in the respective fleets of interest. Regarding French experiments, this is a consequence of the sampled vessels targeting monkfish. This sub-fleet is the largest contributor to cuckoo ray discards but operates more offshore and has greater tow times than the average otter trawler from the target fleet. In the Irish experiment, the slightly deeper mean depth in operations conducted by Vessel 5 compared to the focus fleet may account for areas fished when targeting *Rajidae*. These factors probably affect discard survival, as shown by the lower survival rates obtained with Vessel 2 within each season. More generally, the differences between the sampled fishing operations, in terms of fishing practices and environmental conditions, are reflected in the variability of survival rates. Despite the complexity of disentangling the relative influence of these conditions which are often correlated, these results highlight the importance of assessing discard survival in multiple seasons and vessels when aiming to produce representative estimates of discard survival rates. Finally, the high numbers of vitality measurements during the French experiments contributed to the robustness of conclusions regarding the estimated survival rates.

Ideally, control individuals would only be exposed to stresses associated with holding conditions they share with test individuals. One option is to use individuals previously acclimated to captivity that would be transferred onto the fishing vessels for the collection of test individuals and then maintained in the same holding facilities as other individuals(Noack et al., 2020). Due to the unavailability of acclimated cuckoo rays, it was decided to resort to collecting control individuals during the trip with short fishing operations to limit the extent of traumas incurred by the fish. This is common practice in survivorship studies (e.g. Depestele et al., 2014; van der Reijden et al., 2017).

Most published survivorship studies have high survival of control individuals, while here a relatively large proportion (from 20% to 65%) did not survive until the end of the observation period. Survival rates of controls must be considered when interpreting the results of this study. The origin of mortality in controls determines the interpretation of results. This mortality can either:

- have a neutral effect, by being completely independent of the survival of test individuals. This occurs when the individuals used as controls do not strictly conform to the definition of controls, i.e., when their survival is influenced by other factors than holding conditions they share with the test individuals (e.g., the catching process).
- be associated with an underestimation of survival rates of discarded individuals. This is the case when survivorship of all individuals is affected by holding conditions.

In the first situation, no correction of the estimated survival rates of test individuals should be applied, while the second situation opens the possibility for a correction. We must therefore carefully assess which situation relates to our case study the most.

The collection method for control individuals calls for a consideration of a non-conformity hypothesis to the definition of controls. Due to the depths at which control individuals were collected (minimum 95 m in the Irish experiment, 130 m in the French experiments), the haul duration could not be brought under 20 minutes and some traumas related to the catch operation are therefore expected. This hypothesis is supported by the notable improvement in the survival of controls in the summer compared to the winter. A tarpaulin-covered cod-end was used to collect controls during summer that maintained fish in water and reduced skin abrasion as well as compression in the net. If the non-conformity hypothesis were to be accepted, mortality among control individuals should not play any role in the interpretation of estimated survival rates for test individuals. But onshore holding conditions were also improved by the addition of a layer of sand at the bottom of the tanks and a partial shading of the tanks. This makes it impossible to rule out the occurrence of a higher mortality generated only by the more adverse conditions during the winter fishing operations.

The hypothesis of the holding conditions having affected the survivorship of both control and test individuals is supported by the existence of an apparent stable ratio of survival rates between tests and controls, across all experiments for a given vitality category. A larger number of data points would be necessary to test the statistical significance of these constant ratios, though. Constant ratios would suggest that non-optimal holding conditions similarly affect test and control survival. This suggests that a survival rate correction can potentially be applied. In a case where different experimental conditions have led to differences in the survival of control individuals but with a constant ratio of test to control survival, we propose a way to correct for the influence of non-optimal holding conditions on survival. A simple correction factor, equal to the inverse of the control survival rate, could be initially applied to compensate for the underestimation of delayed survival in test individuals.

Depending on whether the proposed correction factor is applied, discarded cuckoo ray survival rates are estimated between 3.6% and 32.5%. These estimated values per trip vary as a function of area, season and vessel. We are aware that this simple correction would be imperfect if sub-optimal holding conditions were to have more or less marked effects on test individuals' survival depending on their vitality. In such a case, more pronounced detrimental effects would be expected on individuals in poorer condition. Nevertheless, we believe that applying a unique correction factor provides an instructive estimation of the dimension of the upper bound of survival rates.

In addition, the observed mortality in control individuals probably results from a combination of causes. Separating the relative influences of parameters on sampled fish survival cannot be achieved here but should be considered in a meta-analysis involving multiple survivorship experiments, preferably on a unique species.

The estimated survival rates of cuckoo ray discards obtained here appear low compared to other estimates for commercial skate species. For example, after three weeks of monitoring in holding facilities Van Bogaert et al. (2020) indicated survival rates of 71.6% and 86.4% for thornback (*Raja clavata*) and blonde rays (*R. brachyura*) caught using twin-rigged bottom trawls in the eastern English Channel and southern North Sea. Additionally, in a small bay enclosed within the Bay of Biscay, Morfin et al. (2017), based on acoustic tagging, concluded in a minimal estimate of 49.5% survival for undulate ray (*R. undulata*) discarded by a single-rigged otter trawler. Our results are consistent with the suspicion of lower discard survival for cuckoo ray. However, the relative contributions of a higher sensibility specific to cuckoo ray and the consequence of particular fishing conditions cannot be separated. Indeed, in the aforementioned studies, trawl hauls were conducted in shallower depths and shorter haul duration, two factors known to influence vitality and hence discarded fish survival (e.g. Benoît et al., 2010). Data on fishing operations simultaneously catching one or several skate species with documented survival rates and cuckoo ray would help disentangle the relative influence of species sensitivity and fishing conditions.

A partial answer to this is brought by studies comparing the vitality or survival of discards of various skate species in the same fisheries (Van Bogaert et al., 2020). Van Bogaert et al. (2020) reported proportions of thornback and blonde ray with good or excellent vitality superior to 60% for three types of fishing gear: otter trawl, beam trawl and gillnet. Though some variability existed between gears, survival rates of individuals maintained in captivity were all over 56%. Based on observations made on the same vessel (Vessel 5) as used in the autumn experiment presented here Oliver et al. (2019) reported frequencies of thornback and blonde ray with good or excellent vitality over 85%. In the same trips, the proportion of cuckoo ray observed with good or excellent vitality was close to 95% (94.8%). Despite some inter-gear differences in the relationships between vitality and final survival, it seems reasonable to expect a final survival of thornback and blonde ray over 56%, which represents almost twice the highest estimate obtained for cuckoo ray in the present study. This strongly suggests a higher mortality of cuckoo ray following discarding by otter trawlers attributable to a greater sensitivity of this species. However, a higher sensitivity of this species to captivity cannot be ruled out.

The low discard survival for cuckoo ray is further supported by results from Valeiras et al. (2019), where their study conducted with an otter trawler in ICES Division 9a showed that none of the rays placed in a tank survived longer than seven days after capture. However, the higher survival rates estimated for cuckoo ray caught using beam-trawl in the western English Channel (34-35%, Catchpole et al., 2017) suggest some influence of fishing conditions on the final estimates. Yet, the results obtained in this other study may also only reflect sampling variability due to the small number of fish observed in this other study (26, caught by one vessel).

Despite being relatively low, the survival rates of cuckoo ray discarded by otter trawlers in ICES subareas 7 and 8 may not constitute a threat to the sustainable exploitation of the stock considered, at least in the short term. Indeed, the most recent assessment of the stock of cuckoo ray in subareas 6 and 7, and in divisions 8.a–b and 8.d (West of Scotland, southern Celtic Seas, and western English Channel, Bay of Biscay) indicates a recent fishing mortality estimated less than half the mortality corresponding to the maximum sustainable yield (ICES, 2022). An estimation of discarded quantities is however necessary to appreciate the consequence of this low survival on the dynamics of the stock.

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Data availability

Additional information regarding sample collection and holding facilities as well as information regarding the representativeness of the sampled vessels and regarding the fit of survival mixture models is available as supplementary material. The data underlying this article will be shared on reasonable request to Loïc Baulier (for French data) or Martin Oliver (for Irish data). Due to privacy issues regarding the commercial vessels participating in this study, only anonymised data may be shared.

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