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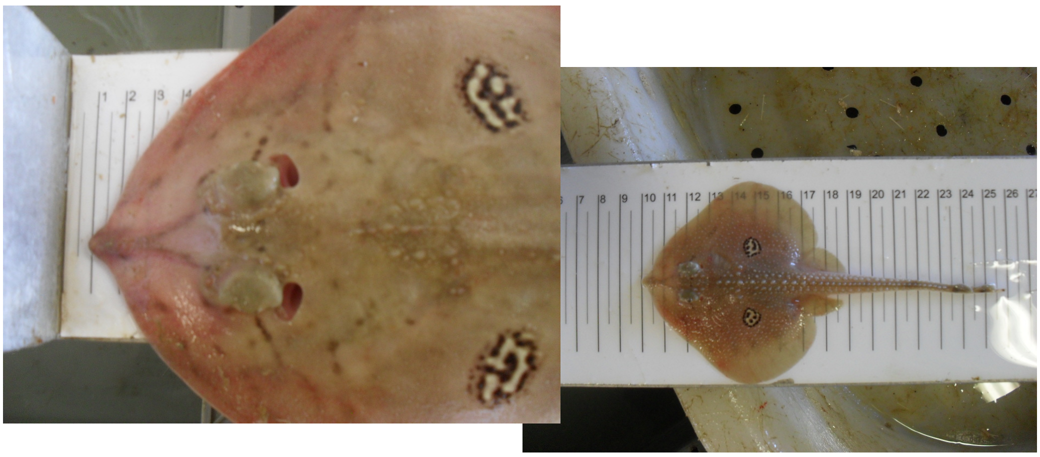
THE SURF PROJECT: survivability of discarded cuckoo rays (*Leucoraja naevus*) in French bottom trawl fisheries



Funding :

Context

The European Union (EU) landing obligation came into full force in 2019 after a gradual phase-in period. Since then, exemptions have been granted under the high survivability of discard provision for several stocks and fisheries. Among them are temporary three-year exemptions for skate and ray stocks, which are managed in EU Atlantic waters based on total allowable catch (TAC). For these exemptions to be extended, scientific evidence needs to show that survival is indeed high. Past work (e.g. Catchpole et al. 2017) has suggested that the survival of the cuckoo ray (*Leucoraja naevus*) may be lower than that of other skates and rays.

The cuckoo ray is the most landed ray species in the Celtic Sea and the Bay of Biscay. It is thus of major economic importance for many fishers. The International Council for the Exploration of the Sea (ICES) provides advice on the cuckoo ray stock in subareas 6 and 7 and in divisions 8a, b, and d. The stock is managed based on the two common TAC values for Rajiformes in the area. In this general zone, cuckoo rays are mainly landed by French vessels (77% of landings between 2017 and 2019). Most are captured during bottom trawling directed at other demersal fishes. From 2017 to 2019, bottom trawling accounted for 89% of cuckoo ray landings in subareas 7 and 8 (source: WGEF data provided to ICES in 2020).

Under current regulations (i.e., Commission Delegated Regulation [EU] 2020/2015), landing obligation exemptions related to cuckoo rays caught by bottom trawlers are set to expire on 31 December 2023 in ICES subareas 6 and 7 and on 31 December 2021 in ICES subarea 8.

The SURF project (*SUrvie des rejets de Raie Fleurie*) sought to estimate the survivability of discarded cuckoo rays captured by French bottom trawlers that target demersal fishes and that operate in subareas 7 and 8. The core of this fishery is located in the Celtic Sea and in the northern Bay of Biscay; it straddles the boundary between subareas 7 and 8 (Figure 1).

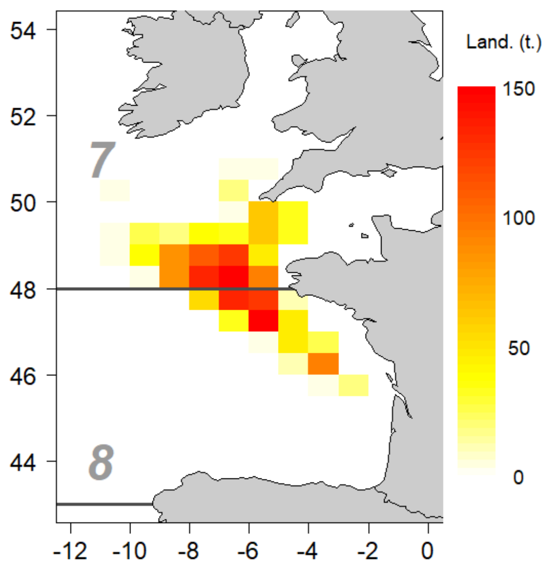


Figure 1: Cuckoo ray landings by French bottom trawlers per ICES statistical rectangle in ICES subareas 7 and 8 in 2019 (sources: logbooks, auction data, and VMS data).

Because mortality resulting from fishing and discarding processes can be delayed, this study followed the recommendations of the Working Group on Methods for Estimating Discard Survival (WGMEDS; ICES, 2020). Two experiments were thus performed:

- A vitality experiment in which four vitality indices were estimated for cuckoo rays fated for discard **under fishing conditions representative of fleet activity**
- A captivity experiment in which captive cuckoo rays were used to examine the relationship between vitality and discard survival during three weeks

The results of the two experiments were employed to estimate the longer-term survival of discarded cuckoo rays at the fleet scale.

Materials and methods

Fishers were recruited to participate in this study. The research was performed using three bottom trawlers based out of Le Guilvinec (western Brittany), the main port associated with French landings of cuckoo rays (55% in 2019 according to SIH[1] data), and one bottom trawler based out of La Cotinière (a village between Nantes and Bordeaux). During the study, these vessels were rigged with twin otter trawls equipped with 100-mm diamond mesh cod-ends.

Vitality experiment

The vitality of cuckoo rays fated for discard was characterised during commercial fishing trips by the bottom trawlers to subareas 7 and 8. During these trips, demersal fishes were targeted. A scientific observer was assigned to the different trawlers and participated in two fishing trips per season (winter, spring, and summer). In this way, at least two-thirds of the trawlers' fishing operations were sampled. For each sampled operation, the observer randomly selected up to 20 cuckoo rays (whenever possible) that were to be discarded. Their vitality was assessed using four different indices. The first was a semi-quantitative index (SQI) that was based on four ordinal vitality classes defined by Benoît et al. (2010) (Table 1). Assessments of animal condition had to be performed quickly, typically within a few seconds.

Table 1: Description of the different categories of the semi-quantitative vitality index (SQI), 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/ Dead	D	No movement of body or spiracle opening (no response to touching or prodding)

Three quantitative indices were used to further characterise cuckoo ray vitality:

- 1) The reflex action mortality predictor (RAMP) score(Davis, 2010): in this metric, the impairment of specific reflexes is scored. Here, four reflexes were evaluated in a fixed sequence (Table 2). Each received a binary score: 0 = normal response, 1 = impaired response. The response to the stimulus must be evident and occur within five seconds, otherwise a score of 0 is given. The responses for each individual are summed, and the total is standardised to fall between 0 and 1.

[1]*Système d'Information Halieutiques*: French Research Institute for Exploitation of the Sea (IFREMER) network for collecting and processing French fishery data

- 2) An injury score (Van Bogaert et al., 2020): in this metric, the severity of different injuries are scored. For each injury type, severity is scored on a scale of 0 to 3, depending on the relative surface area affected by the injury (Table 3). The scores for each individual are summed, and the total is standardised to fall between 0 and 1.
- 3) A combined index: this metric took the mean of the values of the two above indices.

Table 2: Description of the RAMP index (Van Bogaert et al., 2020)

Reflex	Stimulus description	Unimpaired response
Bodyflex	Hold the ray by its anterior end of its disc in a horizontal, plane position, one hand on either side of the mid-line (dorsal side facing up); larger specimens may be supported also by their posterior end	Moves/actively contracts its pectoral fins, its tail and body
Tailgrab	Gently grab the ray by the tip of the tail between thumb and index finger	Actively struggles and attempts to swim away
Spiracles	Observation of the opening and closing of the valves inside the spiracles	The spiracles actively open and close
Startle touch	Tap gently but firmly behind the eyes and spiracles using a fingertip	Quickly and temporarily retracts its eyes

Table 3: Description of the injury index (Van Bogaert et al., 2020)

Injury type	Description	Severity scale
Bleeding head	Point bleeding and/or bruising of the head	0: No injury
Bleeding body	Point bleeding and/or bruising of the body	1: damaged surface < 10%
Bleeding tail	Point bleeding and/or bruising of the tail	2: 10%< damaged surface < 50%
Open wounds	Areas where skin was removed and underlying tissue can be observed	3: 50% < damaged surface
Fin damage	Areas of the fin that were damaged and/or split	

All these indices were assessed when the catch was being sorted by the crew. Consequently, the amount of time that animals were exposed to the air was similar to that experienced by fish under normal commercial conditions prior to discard.

Unlike the SQI, the RAMP score could differentiate between moribund and dead rays. An individual was declared dead when all evaluated reflexes were impaired. The immediate rate of mortality (i.e., calculated from the number of dead animals at the time of sorting) was then estimated from these commercial fishing trips.

Sampling took place on two distinct vessels each season during one fishing trip (Table 4). One was always Vessel A, which was also used for the captivity experiment. The winter trip of vessel B was split into two subtrips for logistical reasons.

Table 4: Description of the commercial fishing trips

Season	Vessel	Dates of fishing trips
Winter	Vessel A Vessel B	17/01/2020 to 29/01/2020 16/12/2020 to 21/12/2020 and 03/02/2021 to 15/02/2021
Spring	Vessel A Vessel D	10/04/2019 to 23/04/2019 01/05/2019 to 08/05/2019
Summer	Vessel A Vessel C	01/08/2020 to 12/08/2020 13/07/2020 to 20/07/2020

Captivity experiment

Cuckoo rays to be discarded were collected during three dedicated fishing trips aboard vessel A in the summer of 2020 (from August 30 to September 5). During each of these trips, the cuckoo rays were deposited every other day at the port of Brest. They were then taken to an aquarium facility (Océanopolis) for monitoring.

A total of 29 cuckoo rays could be maintained at a time on vessel A. Thus, each trip, 5 control and 24 test animals were collected by two onboard scientists. During the collection trips, fishing operations were conducted as during the commercial trips (i.e., in terms of location, duration, sorting procedures). A stratified sampling design based on SQI was used: six individuals in each category were sampled during each trip. Data were also collected to calculate the three other indices for these individuals (Tables 2–3). As previously mentioned, it was possible to distinguish between dead and moribund individuals based on RAMP index values. Hence, only living cuckoo rays in category D of the SQI were kept in captivity.

To reduce levels of pathogen transmission and stress, cuckoo rays were kept in individual opaque boxes with an open water circulation system. The boxes were stored on racks in groups of four or five. Sea water was pumped into a plastic barrel in which variable-flow water pumps were immersed; there was one pump per rack. To control the inflow for each box, a ball valve was added to every water supply hose. The cuckoo rays thus experienced an equal degree of water inflow. An air stone was placed in each box to ensure that the animals did not experience oxygen stress. General stress was also reduced via the addition of an opaque hinged lid to every box. The racks were set up under a roofed part of the deck to prevent direct sun exposure.

The five control animals collected during each trip were used to assess whether living in captivity induced mortality (aboard the vessel and in the aquarium facility). At the time, no public aquariums in the vicinity kept cuckoo rays. Collection took place at the beginning of each two-day trip during short hauls (duration: 22 min to 1 h 8 min). Procedural improvements were made for the summer phase—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 were used as controls.

Upon arrival in Brest, the cuckoo rays were transferred to the aquarium facility in a van equipped with a large tank and an oxygen concentrator. The trip was 4 km long. When the cuckoo rays arrived at the aquarium, their vitality was again evaluated. They were then placed in outdoor circular tanks (volume: 20 m^3) made of resin. The tanks were protected from direct sunlight by a roof and were covered with a tarpaulin to reduce skin abrasion of the animals against the bottom. The water renewal rate was 10%/h, and the recirculated water passed through a mechanical sand filter. In the summer, the water temperature was maintained at 13°C, which is about the same temperature as the water in which the cuckoo rays were caught.

There was a winter phase of the experiment, but mortality in the control group was 85.7%. The causes could not be ascertained and, consequently, **the results of the winter captivity phase were not used to calculate delayed mortality.** To reduce potential contributing sources of stress, the tank setup was modified for the summer phase. A layer of sand was added to the bottom of the tanks to allow the cuckoo rays to bury themselves. Furthermore, shade cloths were placed over the tanks; they covered half the water surface, providing additional shelter.

All fishing trips conducted in relation to this study were made to the fleet's habitual fishing grounds (Figure 2). The environmental, technical, and biological conditions of each sampled fishing operation were documented by the onboard scientists in charge of sampling. The same person carried out the vitality assessments onboard and at the aquarium facility.

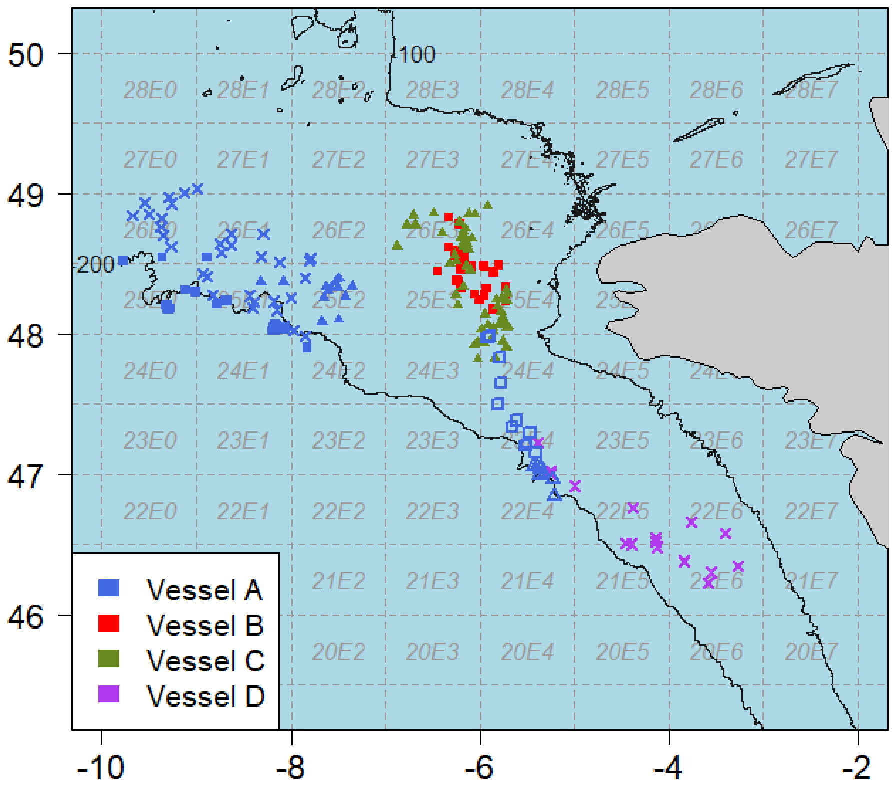


Figure 2: Sites of fishing operations during commercial fishing trips (filled symbols) and collection trips (empty symbols). Triangles: winter; crosses: spring, and squares: summer.

Estimating discard survival

Discard survival was estimated using the following equation:

Survival = (1-immediate mortality) x (1-delayed mortality)

Immediate mortality was estimated from the results obtained during the commercial fishing trips. Delayed survival was estimated from the results of the summer phase of the captivity experiment. A

Weibull mixture model was used to establish the relationship between survival and vitality (Benoît et al., 2015; Farewell, 1982). This model describes both the survival time of the individuals adversely affected by the fishing operation and the probability to survive from the fishing operation. The first process is modelled using a two-parameter Weibull distribution, where α and γ are the scale and shape parameters, respectively. The second probability is modelled using a Bernoulli law whose parameter π is equal to delayed mortality. As a result, the survival probability of any discarded individuals as a function of time since discard *S(t)* can be expressed by the following equation:

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

As time *t* approaches infinity, survival probability converges towards 1-π.

To characterise the relationship between vitality and delayed survival, all the indices were included as explanatory variables in models estimating the above parameters:

$$\log(\alpha_i) = a_\alpha + b_\alpha X_i$$

$$\log(\gamma_i) = a_\gamma + b_\gamma X_i$$

$$\text{logit}(\pi_i) = a_\pi + b_\pi X_i,$$

where X_i is the value of a vitality index (SQI, RAMP, injury, or combined) for an individual *i*. A total of 29 models were tested; their structure varied depending on whether a parameter was treated as a constant or as the function of a vitality index. Models were compared using their predictive power and the Akaike criterion (AIC) (Appendix A).

Finally, survival was estimated for each vessel and season. These figures were obtained by combining the estimates of immediate mortality and of delayed mortality, predicted based on the vitality observed during the commercial fishing trips.

Influence of fishing conditions on survival

As environmental, technical, and biological conditions were documented for each fishing operation, it was possible to assess the influence of various factors on cuckoo ray vitality.

The influence of fishing conditions on survival was assessed by analysing the relationships between the best survival predictor amongst the four vitality indices (as a proxy of survival) and the following variables:

- Haul duration
- Fishing depth
- Catch weight
- Duration of air exposure
- Wave height
- Air temperature
- Presence of harmful items in the catch (e.g., rocks, boarfish, mud) or occurrence of an incident during the haul, forcing the skipper to reel the trawl back in the course of a tow
- Animal sex and total body length

Logistic regression models were performed for all potential linear combinations of these variables; the identity of the fishing operation was treated as a random effect. Model comparison then occurred using AIC.

Results

Vitality experiment

Conditions during the commercial fishing trips

Sampling took place over 164 commercial fishing trips and under various weather conditions, which were mainly affected by the season (Table 5). Air temperature ranged between 5.5°C (in the winter) and 23.2°C (in the summer). This variable served as a proxy for thermal shock, given that water temperature is fairly stable at the depths (> 120 m for all seasons) where animals are caught. Wave height varied considerably among trips, ranging from flat (0 m) to tall (4 m).

There was some variability in haul duration and fishing depth among vessels, but it did not translate into seasonal differences.

The duration of air exposure was also relatively constant among seasons and vessels, with one exception. At the end of one spring fishing operation, the crew had to repair a trawl after the catch was hauled in. Consequently, sorting was delayed an hour.

Table 5: Characteristics of fishing operations during the commercial fishing trips

Characteristics	Season	Mean (range) during the vitality experiment	Mean (range) for the fleet
Vessel length		22.7 m (20.4–24.9 m)	21.4 m (14.4–38.0 m)
Vessel power		471 kW (385–600 kW)	428 kW (209–954 kW)
Haul duration	Winter Spring Summer	4h42’ (2h40’–6h30’) 5h01’ (3h00’–6h10’) 4h45’ (3h30’–7h45’)	4h43’ (1h25’–7h40’)
Fishing depth	Winter Spring Summer	147 m (120–300 m) 165 m (120–290 m) 230 m (120–500 m)	135 m (53–380 m)
Catch weight	Winter Spring Summer	402 kg (150–1100 kg) 544 kg (250–1100 kg) 489 kg (250–1200 kg)	493 kg (53–2070 kg)
Wave height	Winter Spring Summer	2.3 m (1.0–4.0 m) 1.4 m (0.0–4.0 m) 0.8 m (0.5–1.5 m)	
Air temperature	Winter Spring Summer	11.3°C (5.5–16.5°C) 13.9°C (10.6–19.5°C) 19.2°C (16.2–23.2°C)	
Duration of air exposure	Winter Spring Summer	30’ (12’–54’) 36’ (15’–113’) 33’ (12’–63’)	

Vitality of cuckoo rays sampled during the commercial fishing trips

A total of 1,720 cuckoo rays (941 males and 779 females) were sampled over the three seasons, in the course of the six commercial fishing trips. Total body length (TL) ranged between 15 and 64 cm.

In this study, data on cuckoo ray vitality were collected under conditions representative of the normal fleet activity during which most cuckoo rays are captured (e.g., in terms of vessel power and length, haul duration, catch weight, and TL). This representativeness was assessed/ensured through comparison with data collected with ObsMer (the French onboard observation programme) in 2017–2019 and for French trawlers targeting demersal fish in ICES subareas 7 and 8. One potential exception was fishing depth in the case of vessel A. Some commercial fishing operations were conducted deeper (i.e., greater mean fishing depth) than the range covered by ObsMer sampling in recent years.

Based on the SQI, in the winter (when weather conditions were harsher), a mean of 31.0% of cuckoo rays were in excellent or good condition; this mean was 41.4% and 51.5% in the spring and summer, respectively (Table 6). There were differences among vessels (not shown), where vitality was significantly lower for animals captured by vessel A over all three seasons.

A similar result was seen with the RAMP index: mean vitality was lower in the winter compared to the spring and summer (Table 7). Across all seasons, the same pattern was seen in the reflex-specific responses: impairment was most frequent in the "tailgrab" test, followed by the "bodyflex", "spiracles", and "startle touch" tests. The RAMP index values revealed seasonal variability in immediate survival: 82.4% ($CI_{95\%}$ = (78.8%, 85.6%)) of cuckoo rays remained alive on deck in the winter versus 78.5% ($CI_{95\%}$ = (75.6%, 81.1%)) in spring and 71.9% ($CI_{95\%}$ = (66.8%, 76.6%)) in the summer.

Values for the injury index were similar, on average, in the winter and summer and were comparatively lower in the spring (Table 8). Most of the cuckoo rays had one or more injuries, but the presence of injuries depended on the season. In the winter, only 1.1% of individuals were injury free, versus 2.6% in the summer. The most frequent injury was "Bleeding body", which was not surprising given the body's relative surface area.

The same seasonal differences as for the SQI and RAMP scores were observed for the combined vitality score (Table 9). The results of the RAMP and injury scores appeared to be consistent and potentially complementary as they were positively, albeit moderately, correlated (r = 0.52). Hence, the combined index could convey a greater amount of information about vitality. Moreover, the values of the combined index and the SQI were strongly correlated.

Table 6: Vitality across seasons during the commercial fishing trips as assessed using the SQI. Data from the different vessels were equally weighted within seasons.

Season	A (excellent)	B (good)	C (poor)	D (moribund/dead)
Winter	6.7%	24.3%	45.2%	23.7%
Spring	14.1%	27.3%	36.8%	21.8%
Summer	18.8%	32.7%	27.1%	21.3%

Table 7: Impairment frequency observed for each reflex and mean RAMP scores across seasons during the commercial fishing trips. Data from the different vessels were equally weighted within seasons.

Season	Bodyflex	Tailgrab	Spiracles	Startle touch	RAMP score
Winter	67.1%	79.6%	27.3%	12.6%	0.47
Summer	47.1%	69.8%	24.6%	16.2%	0.39
Spring	60.8%	69.2%	22.3%	13.4%	0.41

Table 8: Injury frequency and mean injury score values across seasons during the commercial fishing trips. Data from the different vessels were equally weighted within seasons.

Season	Bleeding—Head	Bleeding—Body	Bleeding—Tail	Open wounds	Fin damage	Injury score
Winter	62.4%	95.3%	75.1%	32.0%	28.3%	0.28
Spring	47.0%	76.7%	64.1%	26.4%	17.9%	0.21
Summer	58.6%	92.6%	66.8%	32.8%	26.8%	0.27

Table 9: Mean combined score across seasons during the commercial fishing trips. Data from the different vessels were equally weighted within seasons.

Season	Combined score
Winter	0.28
Spring	0.21
Summer	0.27

Captivity experiment

Given the high mortality observed during the winter phase of the captivity experiment, catch and captivity conditions were modified moving forward to improve the survival of the control animals. During the summer phase, three cuckoo rays died while aboard the vessel; another died after 14 days in captivity. The mortality rate was thus 20% ($CI_{95\%}$ = (0%, 37.9%)) (Figure 3). While this rate was still appreciable, it was much lower than that during the winter phase. Therefore, only the results from the summer phase were used to establish the relationship between vitality and delayed survival.

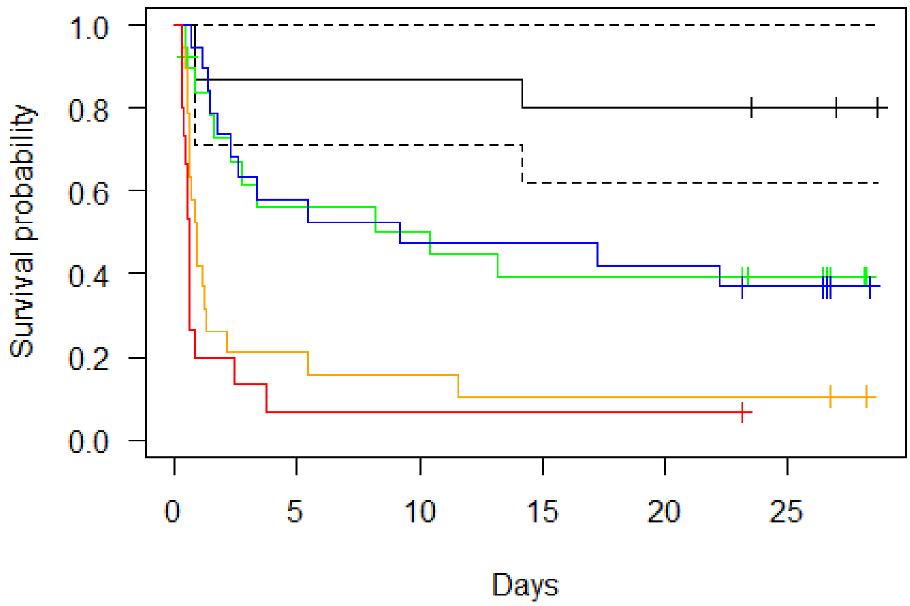


Figure 3: Kaplan-Meier curves for the control (black line) and test (coloured lines) cuckoo rays during the summer phase of the captivity experiment. For the control animals, the dashed lines represent the 95% confidence intervals. For the test animals, each curve corresponds to an SQI vitality class: green: excellent, blue: good, orange: poor, and red: Moribund.

Among the test animals, the average RAMP score values best predicted delayed survival (estimated prediction error = 0.192; Appendix A). The performance of the other indices was slightly weaker, with the injury index in last place (Appendix B).

The predicted survival curves converged well within the monitoring period (Figure 4). This model estimated that delayed survival was between 0.38 and 0 for the entire range of RAMP index values (0–1).

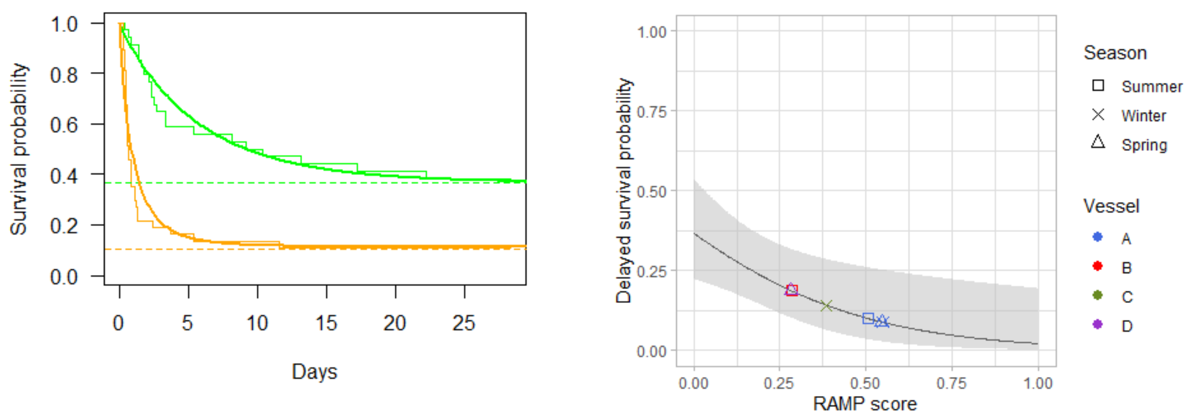


Figure 4: Left—Kaplan-Meier curves showing survival over the captivity period for two RAMP score values. Green: 0, orange: 0.5. Right—Delayed survival (corresponding to the asymptotic values) as a function of RAMP index value. The shaded area represents the 95% confidence interval. The points on the curve are the values associated with the different vessels and seasons.

The overall probability of survival was estimated by combining the immediate survival probabilities from the vitality experiment and the delayed survival probabilities (predicted by the RAMP score values) from the captivity experiment.

Table 10: Estimated cuckoo ray survival (and 95% confidence intervals) for each vessel and season.

	Winter	Spring	Summer
Vessel A	11.7% (11.1%, 14.3%)	12.2% (11.9%, 14.0%)	14.7% (13.3%, 17.7%)
Vessel B			21.7% (20.5%, 24.3%)
Vessel C		21.7% (20.9%, 23.9%)	
Vessel D	17.4% (16.8%, 19.8%)		

Across seasons and vessels, the survival rate of discarded cuckoo rays was predicted to be 11.7–21.7% (Table 10).

Even though survival was slightly lower in the winter, there was greater variation among vessels than among seasons.

Influence of fishing conditions on survival

Because of its stronger predictive power, the RAMP index was used as a proxy for survival when investigating the latter's relationships with fishing conditions.

When all the data were considered, the best-fit model (i.e., with the lowest AIC) contained six variables and explained 13% of total deviance (Table 10). The six variables were positively correlated with the RAMP score values (i.e., negatively correlated with survival). Haul duration, fishing depth, wave height, air temperature, and the duration of air exposure displayed significant effects.

When only data from vessel A were considered (i.e., the only vessel used in all three seasons), the best-fit model also contained six variables but only explained 5% of total deviance. Unlike with all data, fishing depth was not retained. Another difference is that TL and the occurrence of an incident during the haul were retained and were, respectively, negatively and positively correlated with the RAMP score values.

*Table 10: Estimated effects (and standard error [SE]) of the variables retained in the best-fit model for survival that included the RAMP index values. The p-values were obtained from the Student's t-tests performed for each coefficient: *** = <0.001, ** = <0.01, * = <0.05, and . = <0.1.*

		Coefficient (SE)	*p-value*
All vessels	Haul duration	0.56 (0.08)	***
	Fishing depth (log transformed)	0.29 (0.07)	***
	Wave height	0.51 (0.07)	***
	Catch weight	0.09 (0.06)	0.121
	Air temperature	0.25 (0.07)	***
	Duration of air exposure	0.22 (0.06)	***
Vessel A	Haul duration	0.13 (0.07)	.

Wave height	0.51 (0.08)	***
Air temperature	0.23 (0.09)	**
Duration of air exposure	0.28 (0.07)	***
Total body length	-0.17 (0.08)	*
Harmful items or incident	0.30 (0.16)	.

Overall, haul duration was associated with the most variation in survival. On average, the probability of survival increased from 14% to 32% when haul duration was halved (from 6 h to 3 h).

Wave height and fishing depth were also strongly associated with survival, even more so than the duration of air exposure. The latter variable sometimes had very high values (> 2 hours), and survival rate declined quickly over long periods of exposure. Conversely, if air exposure did not exceed 10 min, then the probability of survival was greater than 22%. Only minor differences were associated with differences in air temperature and catch weight.

Discussion

Because of the high mortality rate of control fish during the winter phase of the captivity experiment, only the results of the summer phase were used to estimate the longer-term survival of discarded cuckoo rays in winter and spring. WGMEDS recommends that individuals used in captivity experiments be captured under a range of conditions similar to the one associated with commercial fishing trips. Indeed, the performance of the vitality indices in predicting survival varied depending on fishing conditions. In summer, the higher temperatures on deck may adversely affect vitality as well as survival (Morfin et al., 2017; Uhlmann et al., 2016). In winter, the larger waves may exert stronger constraints on the trawl, leading to greater stress and compression during hauling in particular. These two effects could offset each other and may at least partially affect vitality, as suggested by the seasonal differences seen in this study. However, nothing further can be ascertained. Therefore, because only data from the summer phase were employed, there remains uncertainty with regards to the estimated winter and spring survival rates.

Even though catch and captivity conditions were improved for the summer phase, there was still some mortality—20%—among the control cuckoo rays. While such a level of mortality is not negligible, this finding was nonetheless considered satisfactory because successfully keeping animals collected in deep-offshore environments in captivity presents technical challenges. Since it cannot be determined whether this mortality resulted from traumatisms sustained during capture or from the conditions of captivity (both on board the vessel and at the aquarium facility), it is possible that delayed survival was actually underestimated.

This study found that the four vitality indices had similar predictive powers. However, the RAMP index was slightly better than the others and was therefore used as a proxy for delayed survival. Although it is often used in survival studies, the SQI turned out to be slightly less useful here. Indeed, the survival rates for the top two vitality categories were extremely similar; the same was true for the bottom two vitality categories. As a result, the models utilising the SQI were likely over-parameterised. In this type of research, there are contrasting considerations. On the one hand, it is easier to compare results among studies when the same indices are used. On the other hand, predictive performance can be improved by customising the indices to meet the needs of individual studies.

This study characterised cuckoo ray vitality using an uncommonly large sample size involving several fishing vessels. Differences in vitality were greater among vessels than among seasons. However, sampling by the different vessels was not balanced across seasons. Consequently, the seasonal variation seen may have actually arisen from vessel-specific fishing practices. When the effects of fishing conditions on survival were examined, it was found that variables such as haul duration, wave height, air temperature, and the duration of air exposure had negative impacts. Past research has found that mainly the duration of air exposure has an impact on the survival of the cuckoo ray and other ray species. However, these conclusions are based on experiments conducted at lower depths and during shorter hauls. For example, in a study in the Irish Sea, mean depth and exposure duration were 135 m and 3 h, respectively (Oliver et al., 2019). In a different study carried out in the English Channel and the North Sea, mean depth and exposure duration were less than 50 m and 3 h, respectively (Van Bogaert et al., 2020).

Here, although vessels were chosen to represent the range of fishing conditions encountered by the French trawler fleet targeting demersal fish, this representation could have been improved. Indeed, because vessel A was the only ship whose commercial fishing trips were observed during all three seasons, its relative contribution to the results was larger. If this vessel poorly represented the fleet in some way, it may have biased the overall results. Indeed, the fact that vitality was systematically poorest for vessel A could stem partially from its deeper tows. This vessel fished at greater depths than the vast majority of trawlers sampled by ObsMer (n = 58 vessels), with only 10.4% of fishing operations catching cuckoo ray carried out below 200 m in ObsMer data. Furthermore, all the vessels used in this study were equipped with diamond mesh cod-ends, the most common configuration for this gear. However, long hauls (5 hours 30 min and longer), as carried out by vessel A for this study, are typically associated with the use of optional selective devices, such as a T90 orientation (i.e., the cod-end mesh has been rotated 90°) cod-end (used by vessel A outside this experiment). Because all the vessels taking part in this experiment were requested to use standard diamond meshed cod-ends (for standardisation purposes), the use of a T90 cod-end by a fraction of vessels in the focus fleet has not been reflected in the results. While diamond mesh remains the most widespread netting in the focus fleet for this study, the proportion of vessels using T90 cod-ends is gradually increasing. Gear with better selective capacities may reduce total catch, thus positively influencing discard vitality (e.g., by reducing injuries and sorting time).

The mean survival rates estimated for cuckoo rays in this study are lower than those estimated for other ray species in past studies (e.g., Enever et al., 2009; Morfin et al., 2019; Van Bogaert et al., 2020). That said, it is impossible to determine whether this finding is due to a species-specific sensitivity to capture or the fishing conditions themselves. Indeed, in this study, hauls were longer and fishing occurred at greater depths than in studies looking at other species. To date, the only published research with large sample sizes (n=141) for captive cuckoo rays was conducted in ICES Division 9a (Descarsel Project; Valeiras et al., 2019). During that study, no cuckoo rays survived for more than seven days. There were, however, no controls, and immediate mortality was higher (33% versus 22% here).

Conclusion

This study analysed the influence of fishing conditions on the survival of discarded cuckoo rays. Data were collected using a fleet of French bottom trawlers targeting demersal fish in ICES subareas 7 and 8. The values of the variables associated with sampled fishing operations globally reflect the ranges of variation observed at the fleet level. However, the fishing operations from vessel A were sampled under conditions not reflecting the average of the fleet, which may have resulted in lower survival. Consequently, the survival rates estimated from vessel A data should be treated as values at the lower end of the potential range as well.

Based on a large number of samples, the mean survival rate of cuckoo rays captured in bottom trawls when targeting demersal fish in subareas 7 and 8 was estimated to lie between 12% and 22%. When interpreting these results, it is important to account for the uncertainty surrounding the 20% mortality rate for the control animals, which could partially stem from the conditions in the captivity experiment.

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APPENDIX A: SURVIVAL IN CAPTIVITY DURING WINTER EXPERIMENT

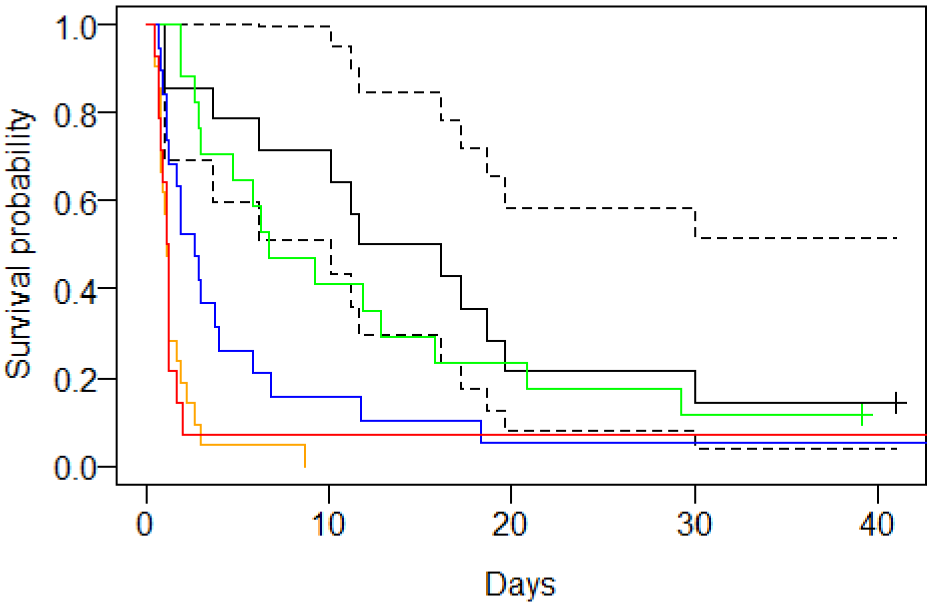

Figure A.1: Kaplan-Meier curves for the control (black line) and test (coloured lines) cuckoo rays during the winter phase of the captivity experiment. For the control animals, the dashed lines represent the 95% confidence intervals. For the test animals, each curve corresponds to an SQI vitality class: green: excellent, blue: good, orange: poor, and red: Moribund.

APPENDIX B: PREDICTION PERFORMANCE OF THE DELAYED SURVIVAL BY VITALITY INDICES

Table B.1: Description of candidate regression models, where X_i is the observed vitality index of ray *i*.

Model name	α	γ	π
M_0	$ln(\alpha_i)=a_\alpha$	$ln(\gamma_i)=a_\gamma$	$logit(\pi_i)=a_\pi$
M_α	$ln(\alpha_i)=a_\alpha+b_\alpha X_i$	$ln(\gamma_i)=a_\gamma$	$logit(\pi_i)=a_\pi+b_\pi X_i$
M_γ	$ln(\alpha_i)=a_\alpha$	$ln(\gamma_i)=a_\gamma+b_\gamma X_i$	$logit(\pi_i)=a_\pi$
M_π	$ln(\alpha_i)=a_\alpha$	$ln(\gamma_i)=a_\gamma$	$logit(\pi_i)=a_\pi+b_\pi X_i$
$M_{\alpha,\pi}$	$ln(\alpha_i)=a_\alpha+b_\alpha X_i$	$ln(\gamma_i)=a_\gamma$	$logit(\pi_i)=a_\pi+b_\pi X_i$
$M_{\gamma,\pi}$	$ln(\alpha_i)=a_\alpha$	$ln(\gamma_i)=a_\gamma+b_\gamma X_i$	$logit(\pi_i)=a_\pi+b_\pi X_i$
$M_{\alpha,\gamma}$	$ln(\alpha_i)=a_\alpha+b_\alpha X_i$	$ln(\gamma_i)=a_\gamma+b_\gamma X_i$	$logit(\pi_i)=a_\pi$
$M_{\alpha,\gamma,\pi}$	$ln(\alpha_i)=a_\alpha+b_\alpha X_i$	$ln(\gamma_i)=a_\gamma+b_\gamma X_i$	$logit(\pi_i)=a_\pi+b_\pi X_i$

Prediction performance

Prediction error of each survival model was estimated by a leave-10%-out cross-validation method, which consists in (i) randomly leaving out 10% of the observations to fit the model, and then (ii) to calculate the corresponding prediction error on the left data. This error was estimated depending on time duration across the whole monitoring period according to the Brier score, adapted to censored data (Gerds and Schumacher, 2006, Graaf et al., 1999). These steps were repeated 200 times and averaged to provide a mean prediction error for the whole monitoring period.

Table B.2: Results of Weibull mixture models with the SQI. For each candidate model (Table B.1) is reported: the Akaike criteria (AIC), the average Brier score estimated by cross-validation (Brier_s), the gain in prediction performance compared to the neutral model M_0 (P_Gain) and the estimated probability of delayed survival for each vitality categories.

Model				Survival probability			
	AIC	Brier_s	P_Gain (%)	A	B	C	D
M_0	643	0.220	REF	0.24			
M_α	629	0.220	+0%	0.23			
M_γ	649	0.220	-+0%	0.24			
M_π	641	0.203	+8%	0.39	0.36	0.10	0.06
$M_{\alpha,\pi}$	629	0.206	+7%	0.39	0.36	0.11	0.07
$M_{\gamma,\pi}$	648	0.204	+8%	0.39	0.36	0.11	0.07
$M_{\alpha,\gamma}$	636	0.209	+5%	0.10			
$M_{\alpha,\gamma,\pi}$	**639**	**0.202**	**+9%**	**0.39**	**0.35**	**0.11**	**0.07**

Table B.3: Results of Weibull mixture models with the RAMP score. For each candidate model (Table B.1) is reported: the Akaike criteria (AIC), the average Brier score estimated by cross-validation (Brier_s), the gain in prediction performance compared to the neutral model M_0 (P_Gain) and the estimated regression factors in the relationship between the probability of delayed survival ($1-\pi$) and the RAMP score.

Model	AIC	Brier_s	P_Gain (%)	$1-\pi=1/(1+\exp(a+b*Score)$	
				a	b
M_0	643	0.220	REF	1.16	0
M_α	616	0.208	+5%	1.23	0
M_γ	645	0.208	+5%	1.16	0
M_π	637	0.197	+11%	0.51	3.38
$M_{\alpha,\pi}$	611	0.196	+11%	0.54	3.27

$M_{\gamma,\pi}$	640	0.198	+10%	0.51	3.40
$M_{\alpha,\gamma}$	617	0.204	+8%	1.81	0
$M_{\alpha,\gamma,\pi}$	**613**	**0.192**	**+13%**	**0.55**	**3.26**

Table B.4: Results of Weibull mixture models with the Injury score. For each candidate model (Table B.1) is reported: the Akaike criteria (AIC), the average Brier score estimated by cross-validation (Brier_s), the gain in prediction performance compared to the neutral model M_0 (P_Gain) and the estimated regression factors in the relationship between the probability of delayed survival ($1-\pi$) and the Injury score.

Model	AIC	Brier_s	P_Gain (%)	$1-\pi$ =1/(1+exp(a+b*Score)	
				a	b
M_0	643	0.220	REF	1.16	0
M_α	639	0.217	+2%	1.17	0
M_γ	644	0.220	+2%	1.16	0
M_π	642	0.210	+5%	0.27	6.58
$M_{\alpha,\pi}$	638	0.213	+3%	0.30	6.39
$M_{\gamma,\pi}$	643	0.210	+5%	0.28	6.50
$M_{\alpha,\gamma}$	639	0.216	+2%	1.21	0
$M_{\alpha,\gamma,\pi}$	**639**	**0.209**	**+5%**	**0.34**	**6.19**

Table B.5: Results of Weibull mixture models with the combined score. For each candidate model (Table A.4.1) is reported: the Akaike criteria (AIC), the average Brier score estimated by cross-validation (Brier_s), the gain in prediction performance compared to the neutral model M_0 (P_Gain) and the estimated regression factors in the relationship between the probability of delayed survival ($1-\pi$) and the combined score.

Model	AIC	Brier_s	P_Gain (%)	$1-\pi$ =1/(1+exp(a+b*Score)	
				â	b
M_0	643	0.220	REF	1.16	0
M_α	617	0.220	+0%	1.23	0
M_γ	645	0.220	+0%	1.16	0
M_π	637	0.203	+8%	0.17	6.01
$M_{\alpha,\pi}$	612	0.206	+7%	0.22	5.84
$M_{\gamma,\pi}$	639	0.204	+8%	0.21	6.03

$M_{\alpha,\gamma}$	619	0.209	+0%	1.22	0
$M_{\alpha,\gamma,\pi}$	**614**	**0.202**	**+9%**	**0.21**	**5.86**