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# Original Article

## Relative survival scenarios: an application to undersized common sole (*Solea solea* L.) in a beam trawl fishery in the Mediterranean Sea

Francesco Masnadi [1,2,‡], Enrico Nicola Armelloni [1,‡], Stefano Guicciardi[1], Giulio Pellini[1], Saša Raicevich[3], Carlotta Mazzoldi[4], Martina Scanu [1], Laura Sabatini[1], Anna Nora Tassetti[1], Carmen Ferrà[1], Fabio Grati[1], Luca Bolognini [1], Filippo Domenichetti[1], Roberto Cacciamani[1], Federico Calì[1], Piero Polidori[1], Gianna Fabi[1], Francesca Luzi[1], Otello Giovanardi[3], Valentina Bernarello[3], Eugenia Pasanisi[3], Gianluca Franceschini[3], Cristina Breggion[4], Elisa Bozzetta[4], Andrea Sambo[4], Giuseppe Prioli[5], Andrea Gugnali[5], Elena Piccioni[5], Fabio Fiori[5], Fabrizio Caruso[5], and Giuseppe Scarcella[1]

[1]*Institute for Biological Resources and Marine Biotechnologies - National Research Council of Italy (IRBIM-CNR), L.go Fiera della Pesca, 60125 Ancona, Italy*
[2]*Department of Biological, Geological and Environmental Sciences, University of Bologna, Piazza di Porta S. Donato 1, Bologna, Italy*
[3]*Italian National Institute for Environmental Protection and Research (ISPRA), Loc. Brondolo, Chioggia 30015, Italy*
[4]*Department of Biology, University of Padova, Via U. Bassi 58/B, Padova 35121, Italy*
[5]*M.A.R.E. S.c. a r.l.—47841, Via Enrico Toti 2, Cattolica, Italy*

**Corresponding author: tel: +39 333 508 8078;* e-mail: *enrico.armelloni@irbim.cnr.it.*
[‡]These authors have contributed equally to this work.

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Fishery discard survival depends on multiple conditions; caution is essential when survival study outputs are employed to support management decisions. The study presents a stepwise procedure, devised to estimate discard survival, that accounts for the variability characterizing commercial fishing practices. The procedure was applied to the first survival study performed onboard *rapido* trawlers targeting *Solea solea* in the Mediterranean Sea. Undersized specimens collected during sorting were assessed for vitality; some were retained for captive observation. The main drivers affecting discard survival at the time of catch sorting (immediate survival) were identified and used to outline four different operational conditions set (scenarios). Immediate survival in each scenario was subsequently modified by applying a hazard coefficient of survival after 5 days of captive observation in relation to each vitality class, thus obtaining relative survival estimates following discarding. Temperature and air exposure duration were found to exert a major effect on survival, with catch weight and seabed type being additional important factors. The relative survival rate showed an aggregate value of 22.9% (10.5–33.4%). Scenario approach can enhance our understanding of the stressors influencing discard survival. The outcomes are discussed to explore the potential applications of the procedure to the identification of mitigation strategies.

**Keywords:** beam trawl fishery, discard survival, machine learning, Mediterranean Sea, *Solea solea*, vitality

## Introduction

In commercial fishing, part of the catch may be discarded due to its low value, poor fish condition, or small fish size (e.g. Bellido *et al.*, 2014). The obligation to land all individuals of species subject to a minimum conservation reference size (MCRS; EC, 2006)—a pillar of the EU Common Fisheries Policy (CFP) that aims to achieve the gradual elimination of discards—has recently been implemented in the Mediterranean Sea [Landing Obligation (LO); EU, 2013]. The success of this measure will largely depend on enforcement mechanisms (Catchpole *et al.*, 2017; Stithou *et al.*, 2019), although the monitoring programme in the Mediterranean is weak and an onboard observer programme is virtually absent (Gilman *et al.*, 2014). The LO includes exemptions for species and fisheries for which there is robust scientific evidence of "high survival" (EU, 2013; Borges and Lado, 2019). The possibility of high survival exemptions has prompted survival assessment studies and the development of methodological guidelines (e.g. ICES, 2014, 2015). Understanding how capture stressors affect discard survival would allow identifying which mitigation options can be adopted and which are unlikely to work (Cook *et al.*, 2019). The approaches devised to quantify discard survival require considerable resources (funding, expertise, and time) that increase as one moves from simpler (time to mortality, e.g. Benoît *et al.*, 2013) to more complex methods (e.g. tagging and biotelemetry techniques; Morfin *et al.*, 2019). Approaches that evaluate fish vitality, such as semi-quantitative assessment (SQA) or quantitative vitality assessment, can be used as survival proxies (e.g. Benoît *et al.*, 2010; ICES, 2014) but do not yield actual survival rates. In isolation, captive observation allows obtaining survival rate estimations that exclude predation (Schram and Molenaar, 2018), whereas the addition of tagging information can provide an estimation that includes post-release predation and natural mortality for particular conditions (Benoît *et al.*, 2020). A proxy to estimate survival in a representative range of conditions (management unit/fishery) can be generated only by combining vitality assessment and captive observation and/or tagging techniques. When the relationship between vitality levels and survival estimates has been determined, the vitality assessment made onboard can be complemented with models using the determined relationships to infer survival (Catchpole *et al.*, 2015). Yet, the relationship between vitality and survival probabilities varies in different environmental and fishing conditions (Kraak *et al.*, 2019), suggesting that the interpretation of data collected in a wide range of situations requires caution.

A "scenario" approach can account for the variability inherent in a given fishery. Grouping data obtained in similar environmental and fishing conditions may enable more accurate survival estimations.

Here, a stepwise machine learning procedure is presented to define "fishing scenarios" according to the main stressors affecting survivability. The procedure was applied to the case study of the common sole (*Solea solea*) fishery in the Mediterranean Sea [northern Adriatic Sea; GFCM Geographical Sub-Area (GSA) 17], an area for which limited information on discard conditions is available (Raicevich *et al.*, 2011, 2014; Tsagarakis *et al.*, 2018). Undersized sole (MCRS, 20 cm) were sampled during a set of commercial fishing trips using a modified beam trawl named "rapido" (Pranovi *et al.*, 2000) according to the fishing practices adopted by the local fleets in conditions representative of local variability (ICES, 2014).

The data collected included dead or alive state at the time of sampling (hereafter, immediate survival), vitality assessment scores and information on environmental parameters and fishing conditions. A subset of specimens was landed and monitored in the laboratory to connect vitality to survival. The outcomes of the case study are discussed to highlight the advantages and limitations of the approach and its potential applications to identify discard mortality mitigation strategies.

## Material and methods

### Study area

The northern Adriatic Sea is the largest continental shelf area in the Mediterranean Sea. It is a semi-enclosed basin where seasonal thermal cycles result in a sea surface temperature range that can exceed 10°C during the year (Artegiani *et al.*, 1997). The bottom largely consists of sandy mud and muddy sand, with a predominance of small grain sizes; depth generally does not exceed 100 m (Santelli *et al.*, 2017). These features provide ideal trawling conditions almost throughout the basin, which is one of the most intensely exploited fishing grounds in the Mediterranean Sea (Eigaard *et al.*, 2017; Ferrà *et al.*, 2018).

The present case study examines the *rapido* trawl fishery targeting common sole, which accounts for 50% of *S. solea* landings in the northern Adriatic Sea (STECF, 2019). The *rapido* gear consists of a box dredge with a rigid mouth rigged with iron teeth (5–7 cm long) along the lower leading edge that mechanically stimulate the benthic organisms, forcing them to rise from the bottom (Hall-Spencer *et al.*, 1999; Pranovi *et al.*, 2000). Its catch therefore consists mainly of organisms living in close contact with the bottom or buried in sediment, such as flatfish (*S. solea*, *Scophtalmus rhombus*, *Scophthalmus maximus*), mantis shrimp (*Squilla mantis*) and shellfish (*Bolinus brandaris*, *Pecten jacobaeus*, *Aequopecten opercularis*). *Rapido* trawlers usually tow four gears simultaneously at a speed of 5–7 knots for 12–24 h a day, depending on local customs, 3–4 days a week according to seasonal regulations. Analysis of Automatic Identification System data according to the method described by Galdelli *et al.* (2019) has demonstrated that *rapido* trawls are usually deployed in fishing grounds characterized by sandy or muddy bottoms and a depth <50 m. Vessels also operate in areas of aggregation of juveniles, especially around the Po River delta (Grati *et al.*, 2013). Under current management measures (national regulations based on EC, 2006), nursery areas are protected by trawling ban encompassing the first three nautical miles from the coast, by a closed season (30–45 days) in late summer and by spatial restrictions (up to 6 nautical miles from the coast) imposed for 60–90 days thereafter. As a result, nursery areas are mainly exploited in the first half of the year, when juveniles account for 20–25% of sole catches in number. In late summer–autumn, when juvenile concentrations are highest, these areas cannot be exploited by trawls and undersized specimens fall to 10–15% of total sole catches.

### Discard sampling protocol

Sampling activities were conducted in the course of 19 commercial fishing trips (Figure 1 and Table 1) onboard three vessels equipped with *rapido* trawls (Table 2) from February 2018 to June 2019. A total number of 151 hauls (5–10 per trip) were sampled. A maximum number of 30 undersized individuals (MCRS, 20 cm) per haul were sampled throughout catch sorting, at the

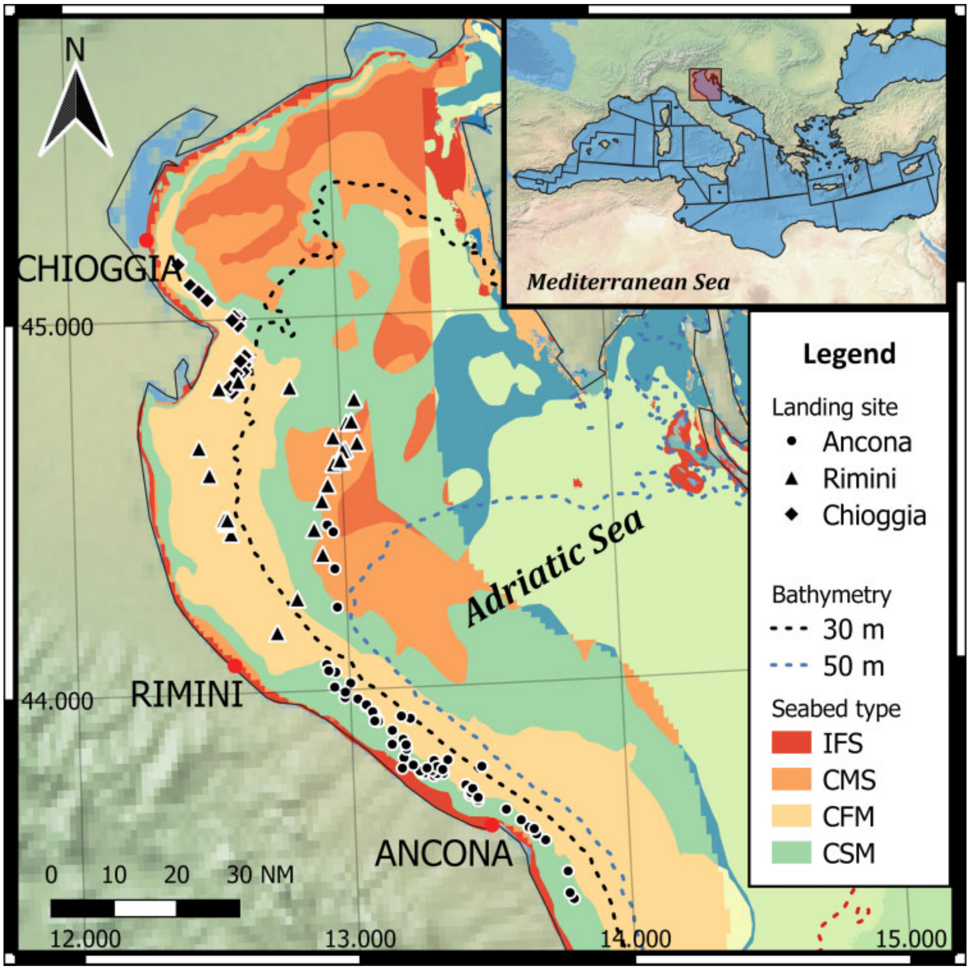


**Figure 1.** Northern Adriatic Sea with seabed habitat (from Populus *et al.*, 2017; filled polygons in background), bathymetry (30 m and 50 m isobaths), and positions of the hauls (symbols indicate the landing site of the vessel employed). Only the seabed types overlapping with the hauls are reported in the legend: Infralittoral Fine Sand (IFS); Circalittoral Muddy Sand (CMS); Circalittoral Fine Mud (CFM); and Circalittoral Sandy Mud (CSM).

time when the fishermen would have had the opportunity to reject them.

The operating conditions recorded for each haul included vessel position, towing speed and duration, air temperature (onboard instrumentation), and bottom temperature (StarOddi Minilog probe; Garðabær, Iceland). Since total catch weight could not be measured by a direct method, to avoid the risks involved in approaching the gear, each haul was photographed from a fixed position, always including an element of known size (usually the stern reel). Processing of the images with ImageJ software (Schneider *et al.*, 2012) allowed calculating the catch volume, which was subsequently categorized as low (L), low-medium (LM), high-medium (HM), or high (H).

The time elapsed since the last trawl was unloaded on deck (air exposure; minutes) and total length to the lower mm was recorded for each sole specimen.

Specimens were then assessed for immediate survival, i.e. the condition of being alive at the time of sampling, where death was the state where they showed no respiratory or reactive behaviour for at least 10 s. Live specimens were then quickly placed in a 300-l saltwater tank (a flow-through system connected to the vessel pump) and assessed for vitality by the SQA (adapted from Benoît *et al.*, 2010). This approach is based on three vitality classes—A (excellent), B (fair), and C (poor)—defined in relation to injury severity, fish activity, and an approximate evaluation of reflex impairment (Table 3). To minimize observer bias, SQAs were performed by trained observers according to a pre-established protocol. After SQA, most live specimens were immediately released, whereas a subset of no more than 5 randomly selected individuals per haul from 15 of the 19 fishing trips were retained for captive observation. These specimens were placed in two 114-l flow-through Board Monitoring Units (BMUs; water flow depending on vessel pump characteristics) endowed with separate, numbered polypropylene compartments (24 cm × 17 cm × 6.5 cm). The BMUs were placed on deck in a position that minimized roll and pitch movements. Once on land, specimens were moved to 600-l Laboratory Monitoring Units (LMUs), provided with a cooling system (Teco, Italy; mod. TK2800), where they were housed separately in numbered compartments (30 cm × 30 cm × 35 cm) filled with artificial seawater (closed circuit water flow, 950 l/h). To avoid contamination, LMU water was sterilized with a UV-C filter (Project, mod. PR-UV 11 W); a skimmer (Bubble-Magus, mod. RockSP2000, 520 l/h) was installed to remove organic particulate. Salinity and temperature were adjusted

**Table 1.** Overview of the fishing trips showing the operating and environmental condition ranges recorded in each trip.

| Date | Landing site | Towing speed (knots) | Air temperature (°C) | Bottom temperature (°C) | Air exposure (min) | Towing duration (min) | Catch weight | Predominant seabed type |
|---|---|---|---|---|---|---|---|---|
| 06 November 2018 | Anc | 6.5–7.1 | 15–20 | 17.4–17.9 | 10–39 | 47–67 | LM–H | CSM |
| 06 December 2018 | Rim | 7.2 | 16.5–28.5 | 15–15.2 | 10–67 | 60–68 | LM–H | CFM |
| 07 February 2019 | Chi | 5.6–6.3 | 1.4–1.5 | 8.8–9.7 | 11–23 | 49–68 | L | CFM |
| 07 May 2018 | Anc | 7 | 14.5–22 | 12.6–16.9 | 22 67 | 46–66 | LM–H | CSM |
| 07 May 2019 | Chi | 5.8–6.2 | 12.8–13.9 | 12.1–13.8 | 22–67 | 51–74 | L | CFM |
| 08 October 2018 | Anc | 6.8–7.5 | 15.5–32 | 20.05–20.6 | 10–55 | 43–55 | HM–H | CSM |
| 16 July 2018 | Anc | 6.8–7.1 | 20–36 | 21.6–23.3 | 10–60 | 29–44 | HM–H | CSM |
| 16 October 2018 | Chi | 6–6.3 | 16–20 | 15.3–19.6 | 10–27 | 53–65 | L | CFM |
| 17 June 2019 | Chi | 5.6–6.3 | 24.3–16 | 12.6–13.8 | 18–28 | 54–69 | L | CFM |
| 17 July 2018 | Chi | 5.9–6.1 | 23–19 | 14.7–17.7 | 19–39 | 55–70 | L | CFM |
| 17 December 2018 | Anc | 6.5–7 | 4–10 | 13.5–15.6 | 10–53 | 56–69 | LM–HM | CFM |
| 18 October 2018 | Rim | 6.4–7.2 | 20–24 | 17–19 | 10–69 | 49–100 | LM | CMS |
| 19 June 2018 | Chi | 5.5–6.1 | 24.9–17.5 | 13.5–17.3 | 17–36 | 54–61 | L | CFM |
| 24 July 2018 | Anc | 7–7.7 | 20–39 | 21.6–23.4 | 10–35 | 30–54 | HM–H | CFM |
| 24 July 2018 | Rim | 7.2 | 28–41.5 | 15.3–16.3 | 10–78 | 58–90 | H | CFM |
| 24 July 2018 | Chi | 5.6–6.1 | 26–19 | 14.9–17.1 | 15–32 | 51–66 | L | CFM |
| 24 October 2018 | Anc | 7–7.2 | 12–22.3 | 19.5–19.7 | 10–32 | 55–59 | LM–HM | CSM |
| 27 March 2018 | Rim | 6.4–7.2 | 7–16 | 9.5–12.5 | 24–51 | 66–97 | LM–HM | CSM |
| 28 March 2018 | Anc | 6.9–7.1 | 3.5–26 | 9.7–10.6 | 20–39 | 38–59 | LM–HM | CFM |

Landing sites: Ancona (Anc); Rimini (Rim); and Chioggia (Chi). Seabed types: Circalittoral Sandy Mud (CSM); Circalittoral Fine Mud (CFM); and Circalittoral Muddy Sand (CMS). Catch weight: L, LM, HM, and H.

**Table 2.** Technical specifications of the vessels and fishing gear.

| Landing site | Ancona | Rimini | Chioggia |
|---|---|---|---|
| Length (m) | 23 | 25.6 | 14.9 |
| Engine power (kW) | 400 | 835 | 187 |
| Tonnage (t) | 86 | 133 | 24 |
| Number of gears | 4 | 4 | 4 |
| Gear width (m) | 4.2 | 3.8 | 2.67 |
| Number of teeth | 44 | 48 | 33 |
| Average fishing speed (knots) | 7 | 7.2 | 6 |
| Average trip duration (h) | 24 | 24 | 13 |

**Table 3.** Criteria used to assess fish vitality according to the SQA method (adapted from Benoît *et al.*, 2010).

| Vitality | Vitality class | Description |
|---|---|---|
| Excellent | A | Vigorous body movement; no or minor external injuries only |
| Fair | B | Weak body movement; responds to touching/prodding; minor external injuries |
| Poor | C | No body movement, but fish can move operculum; minor or major external injuries |

to simulate the conditions recorded in each trip. Water quality was monitored at 24-h intervals by measuring ammonia, nitrates, nitrites, nutrients, and pH. Survival was checked at 12-h intervals for 120 h (5 days). Feeding, with the polychaete *Nereis diversicolor*, began 48 h after transfer to the tanks and continued *ad libitum* at 24-h intervals. Seemingly lethargic fish were gently stimulated and their response assessed. At the end of the experiment, after 120 h, all live specimens were released.

## Methodological approach

The first step of the method estimates the effect of the stressors on immediate discard survival (binomial response variable, "live" = 1; "dead" = 0). The operating condition covariates tested were air exposure (minutes), average towing speed (knots), towing duration (minutes), and catch weight (categorical). The environmental conditions evaluated were thermal shock [$\Delta T$ (°C) = bottom temperature − air temperature] and seabed type (Figure 1: sea habitat descriptors from the EMODNET broad-scale predictive habitat map; Populus *et al.*, 2017). First, the degree of collinearity between the explanatory variables was explored with correlation matrix plots (Zuur *et al.*, 2009). If two or more variables showed a correlation (Pearson's correlation coefficient >0.7), the one considered less relevant for discard survival was removed. Two non-parametric machine learning techniques, Classification Tree (CT) and Random Forest (RF) (Breiman, 1984; Lantz, 2013; Shalev-Shwartz and Ben-David, 2014; Rokach, 2016), are applied to establish relationships among the response variable and the predictor variables. Machine learning flowchart transparencies can be used for applications that generate knowledge to help decision-making (Lantz, 2013). Given a number of explanatory variables, or features, CT and RF determine the most predictive variables and partition the data into groups with different values of the explanatory variables. After yielding a set of tree branches, the algorithm continues to divide the dataset, each time choosing the best candidate feature until a stopping criterion is reached. RF is considered as an evolution of the CT model. A single CT will provide a single prediction result with a single input vector, whereas RF will provide multiple results from a single input since it grows several classification trees. Therefore, RF will use an average output to predict the classification result and provide more reliable results than CT.

Although RF is less prone to overfitting than CT, its results are not simple and immediate to understand; moreover, their unsuitability for graphical display prevents using RF to create scenarios. The use of CT results addresses this problem, albeit by trading a lower reliability for greater simplicity and applicability. For these reasons, RF and CT were applied in parallel to the same data with different purposes. The analysis was conducted using *rpart* (Therneau *et al.*, 2015) and *randomForest* (Liaw and Wiener, 2018) R libraries.

RF analysis was performed to identify the stressors exerting the strongest effect on immediate survival and the marginal effect of the variables on immediate survival (by means of variable importance and partial dependence plot). Subsequently, provided that the results of the two models did not diverge, the CT branches were used to split the dataset into "fishing scenarios", each of which represented a situation characterized by specific environmental and haul-related operating conditions recorded onboard. To prevent overfitting, the minimum number of observations in the final CT node was set at 400. To permit comparisons and assess the benefits of the scenario approach, each of the following steps was performed both on the aggregate data and on each scenario. The immediate survival rate (IS) was calculated as $= \frac{n_{\text{alive}}}{n_{\text{alive}}+n_{\text{dead}}}$, where $n_{\text{alive}}$ is the number of live specimens and $n_{\text{dead}}$ is the number of dead specimens at the time of sampling.

The second step of the method allows assigning a hazard coefficient to each vitality class in each scenario. Our captive analysis lacks two powerful elements of a robust survival study: (i) a control group and (ii) a sufficient duration of captivity observation to assess asymptote survival. Accordingly, the results of the captive observation are to be considered in terms of hazard as measuring relative, not absolute survival. The captive observation survival data were thus taken as a response variable and the vitality class data were fitted as explanatory variables in the Cox proportional hazard model (Therneau and Grambsch, 2000) using the *coxme* R package (Therneau, 2018). The Hazard function describes the probability that a subject that has survived up to time $t$ will die in the next time interval (Moore, 2016) or $h_t = \psi h_0(t)$, where $h_0(t)$ is the baseline hazard and $\psi$ is the parameter accounting for the characteristics of survival distribution. If $\psi = e^{z\beta}$, where Z is a covariate and $\beta$ is a weight coefficient, and then $\psi$ would allow accounting for selected explanatory variables. In our case, the only explanatory variable tested is categorical with three levels (A, B, and C). Level A, in which specimens have the best liveability (ICES, 2014), is used as a reference. Then, for every $i$ level, $\psi i = e^{zi\beta i}$ will be calculated to compare the hazard risk. When statistically significant ($p < 0.05$), $\psi$ was used to calculate the hazard coefficient $sp_i = 1/\psi_i$ the inverse of the probability of a death event occurring in each vitality class. Thus, $sp_i$ is expressed as a ratio relative to the reference vitality class, A.

The final step involves reweighting the IS according to the hazard coefficient calculated for each vitality class in each scenario, to obtain a relative survival (RS) estimation that is based on a set of realistic conditions. The formula applied to each scenario is: $\text{RS} = \text{IS} \times \sum_{i=1}^{n} w_i \times sp_i$, where $w_i$ is the proportion of individuals found in each vitality class $i$ whereas IS and $sp_i$ come from the previous steps. Confidence intervals (*CI*) for the function RS were computed after bootstrapping the $sp_i$ value 9999 times and taking the 95% *CI* of the bootstrap distribution (Efron and Tibshirani, 1991).

## Results

In this case study, 1867 undersized sole specimens were assessed for vitality and 232 were retained for captive observation. After 5 days, 57% of the specimens in vitality class A, 40% of those in class B, and 18% of those in class C were alive. During captive observation, the tank water quality parameters were in the safety range.

With regard to the factors affecting immediate survival, data exploration highlighted a collinearity between catch weight and towing speed, a finding that was supported by a Pearson correlation coefficient of 0.9 (data not shown); therefore, speed was not included in subsequent analyses because, given the small range analysed, it was less informative than weight. The mean node purity reduction in the RF model showed that $\Delta T$ and air exposure were the most important variables, followed by towing duration, catch weight, and seabed type (Figure 2). Partial dependence plots disclosed that longer air exposure and wider negative thermal shock (air temperature higher than bottom temperature) involved a greater probability of immediate death and that a greater catch weight seemed to affect immediate survival adversely (Figure 3a–c). Seabed type, though playing a marginal role in the RF model, exerted an effect; in particular, fishing on sandy-muddy bottoms (CSM) was associated with a slightly lower immediate survival probability compared with the other habitats (Figure 3e). In contrast, the effect of towing duration seemed to show no particular trend (Figure 3d). The CT model also selected $\Delta T$, air exposure, and catch weight as the most relevant features and, based on these stressors, yielded four terminal branches or "fishing scenarios": WRM-LAE, WRM-SAE, CLD-HW, and CLD-LW (Figure 4).

WRM-LAE and WRM-SAE (WRM: warmer; LAE: longer air exposure; SAE: shorter air exposure) shared a negative $\Delta T$ due to the high air temperature typical of summer and involved a different air exposure. CLD-HW and CLD-LW (CLD: cold; HW: higher weight; LW: lower weight) shared a positive $\Delta T$ due to the low air temperature typical of autumn and winter and differed by catch weight. WRM-SAE and CLD-LW can be considered as the scenarios characterized by favourable fishing conditions since,

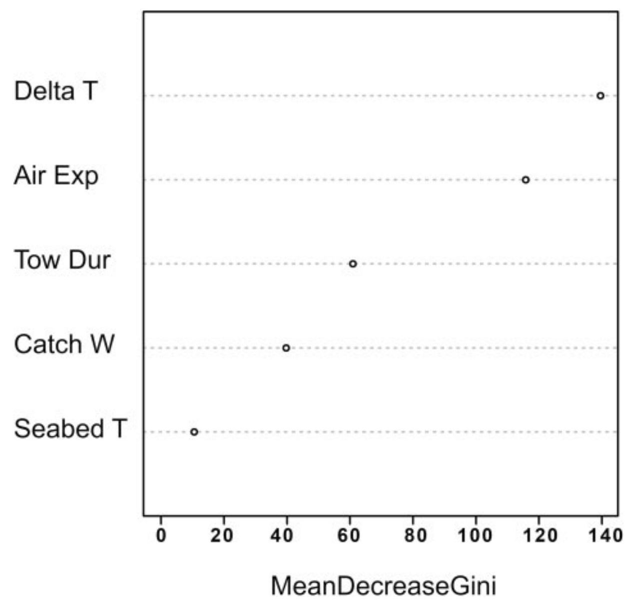


**Figure 2.** Graphical representation of the importance of each variable as calculated by Random Forest analysis. The mean node purity reduction (MeanDecreaseGini) indicates the importance of the relevant variable: the higher the value of the reduction, the more important the variable. Variables: temperature difference between bottom temperature and air temperature (Delta T); air exposure duration (Air Exp); towing duration (Tow Dur); catch weight (Catch W); and seabed type (Seabed T).

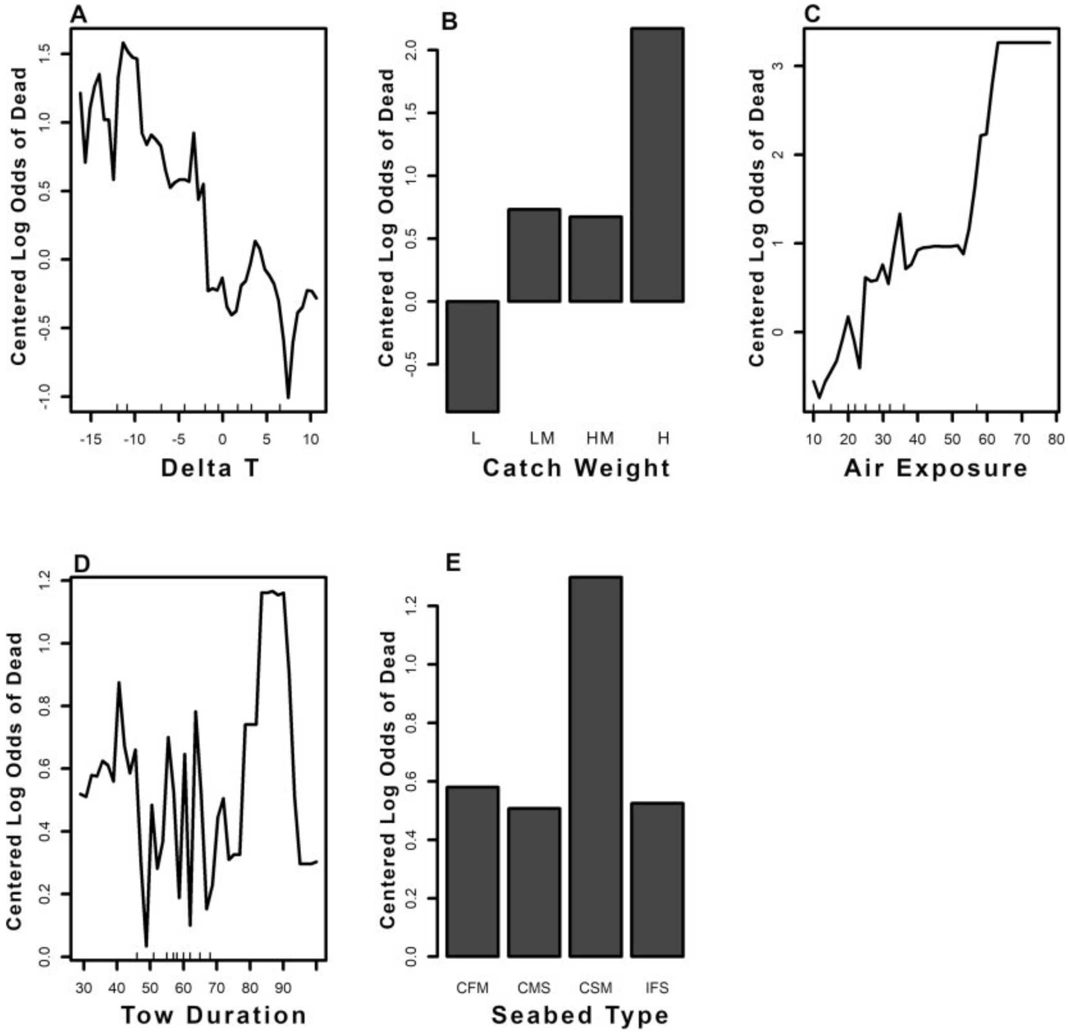


**Figure 3.** Partial dependence plots of Random Forest analysis obtained for each variable: (a) temperature difference between bottom temperature and air temperature (Delta T, °C); (b) catch weight: categories are L, LM,HM, and H; (c) air exposure duration (air exposure, minutes); (d) towing duration (minutes); and (e) seabed types: categories are Circalittoral Fine Mud (CFM), Circalittoral Muddy Sand (CMS), Circalittoral Sandy Mud (CSM), and Infralittoral Fine Sand (IFS). Plots give a graphical depiction of the marginal effect of each variable on immediate survival. *Y*-axis: partial log-scaled probability of death; *X*-axis: value of each variable.

compared with WRM-LAE and CLD-HW they involve respectively a shorter air exposure and a lower catch weight, two stressors that adversely affects survival (Broadhurst *et al.*, 2006).

The IS aggregate value was 41.9%, ranging from 22.1% in the WRM-LAE scenario to 71.6% in the CLD-LW scenario (Table 4). The proportion of A, B, and C vitality class specimens in each scenario ($w_i$) is reported in Table 4.

According to Cox proportional hazard model analysis applied to the aggregate data, the vitality class correlated significantly with survival ($p < 0.05$, Table 4), which declined from classes A to C. The value of $\psi$ indicated that the probability of a death event increased by 1.7 times (95% *CI*: 1.1, 2.6) from A to B and by 3.4 times (95% *CI*: 2.2, 5.3) from A to C. However, this relationship was not found in all the scenarios (Table 4).

Based on the results of the Cox proportional hazard model, RS for the aggregate data was 22.9% (95% *CI*: 19.5; 26.9) and ranged from 10.5% (95% *CI*: 8.6; 13.3) in WRM-LAE to 33.4% (95% *CI*: 27.4; 43.1) in CLD-LW (Table 4). Notably, the lowest RS values were found in WRM-LAE and CLD-HW, the scenarios associated with more unfavourable fishing conditions.

## Discussion and conclusions

The present work aims to facilitate the interpretation of discard survival data by illustrating a method whose intuitive output can help to understand the conditions that maximize discard survival.

The method is based on a stepwise approach, where the results of immediate discard survival assessment onboard are processed with a decision tree algorithm. The subsets obtained by this method are modified with a hazard coefficient of survival after 5 days of captive observation based on the vitality class assigned to specimens in each scenario, thus providing a relative survival estimation after discarding. The decision tree is a widely used data classification technique in data science. To the best of our knowledge, it has never been applied to fishery discard survival. Some features make the CT particularly suitable for our work, whereas others are less advantageous (Lantz, 2013; Rokach,

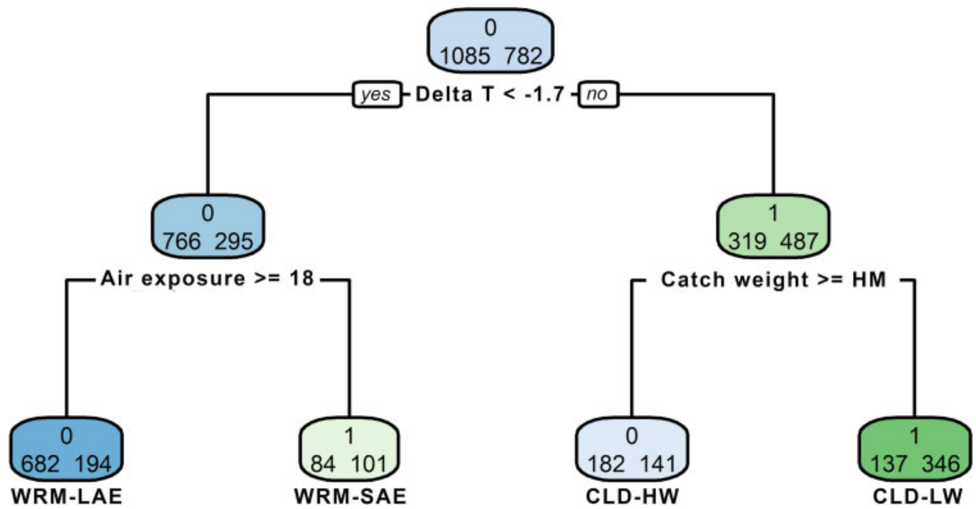


**Figure 4.** Graphical representation of CT analysis. Coloured boxes: top line: 0 and 1 indicate whether there are more dead (0) or live (1) specimens in the box; numbers on the bottom left corner: dead specimens; numbers on the bottom right corner: live specimens; and under each box: split condition for the relevant variable. If verified, the analysis proceeds on the left branch, otherwise on the right branch. At the end of each branch, WRM-LAE, WRM-SAE, CLD-HW, and CLD-LW are the scenario names.

**Table 4.** Summary of main outputs of the analyses of the aggregate data for each scenario.

| Scenario | Short scenario description | IS | Vitality class | % of specimens | Number of specimens | $\psi$(95% *CI*) | RS (95% *CI*) |
|---|---|---|---|---|---|---|---|
| Aggregate | Aggregated data (no division based on different stressors) | 41.9 | A (reference class) | 20.2 | 158 | 1 | 22.9 (19.5, 26.9) |
| | | | B | 35.3 | 276 | 1.7 (1.1, 2.6)* | |
| | | | C | 44.5 | 348 | 3.4 (2.2, 5.3)* | |
| WRM-LAE | Warmer condition, longer air exposure | 22.1 | A (reference class) | 28.8 | 56 | 1 | 10.5 (8.6, 13.3) |
| | | | B | 25.8 | 50 | 4 (1.7, 9.6)* | |
| | | | C | 45.4 | 88 | 4.4 (1.7, 11.2)* | |
| WRM-SAE | Warmer condition, shorter air exposure | 54.6 | A (reference class) | 19.8 | 20 | 1 | 27.3 (23.3, 33.6) |
| | | | B | 44.6 | 45 | 0.72 (0.33, 1.6) | |
| | | | C | 35.6 | 36 | 2.8 (1.23, 6.4)* | |
| CLD-HW | Colder condition, higher catch weight | 43.7 | A (reference class) | 13.5 | 19 | 1 | 19.7[a] |
| | | | B | 32.6 | 46 | 1.3 (0.49, 3.4) | |
| | | | C | 53.9 | 76 | 1.9 (0.77, 4.5) | |
| CLD-LW | Colder condition, lower catch weight | 71.6 | A (reference class) | 18.2 | 63 | 1 | 33.4 (27.4, 43.1) |
| | | | B | 39 | 135 | 1.8 (0.88, 3.9) | |
| | | | C | 42.8 | 148 | 3.4 (1.31, 8.8)* | |

% of specimens: proportion of specimens assigned to each vitality class; number of specimens: number of specimens assigned to each vitality class; $\psi$: probability of occurrence of a death event with statistical significance (*$p \leq 0.05$).
[a]Since $\psi$ values were not significantly different from the reference class, *CI* cannot be computed for this scenario.

2016). Its main pros include a high predictive performance, the ability to account for a variety of data types (numeric, nominal), and for missing values, the absence of assumptions about data distribution and, notably, a self-explanatory output. Its main weaknesses include *instability*, i.e. oversensitivity to non-relevant attributes; *myopia*, i.e. the fact that the splitting criterion ranks the attributes based on the immediate descendants and tends to give priority to those showing high scores in isolation; and *fragmentation problems*, which involve a lower prediction ability under a certain sample size. These constraints were addressed by performing an explorative analysis directed at removing non-relevant correlated variables, by coupling the method to an RF model (which is less prone to myopia), and by limiting the number of divisions to ensure that the subsets consisted of a sufficient amount of data. With these corrections, the method was able to identify specific intervals for the main environmental parameters and fishing variables characterizing the reference fishery and to use them as rules to divide the original dataset into smaller subsets. The subsets were used as scenarios characterized by distinct sets of conditions likely to occur in the field and allowed evaluating survival in consistent operating conditions.

Based on the present case study of *rapido* beam trawls targeting sole in the Adriatic Sea (GSA 17, Mediterranean Sea), the method proposed herein provides an example of how the scenario approach has the potential to enhance managers' understanding of some situations characterizing the fishery and to support the development of mitigation strategies. Analysis of our data highlighted that the chief stressors affecting immediate survival were warmer air temperature and a longer air exposure; a combination of heat shock and longer exposure time has previously been reported to exacerbate physiological stress responses (Davis, 2002; Gale *et al.*, 2013). Another driver of discard survival was high catch weight, which can injure and even kill flatfish in the net (Broadhurst *et al.*, 2006). Further damage may be induced by catch composition: when benthic invertebrates constitute a significant portion of the catch, undersized sole pushed against the codend mesh can be severely injured (Broadhurst *et al.*, 2006). The fishing grounds in the northern Adriatic Sea are characterized by varied benthic assemblages (Figure 1; Populus *et al.*, 2017) with a heterogeneous shellfish density (Santelli *et al.*, 2017). In particular, the sandy mud coastal belt hosts debritic biocoenoses and thanatocoenoses characterized by high rates of gastropods (*Bolinus brandaris*) and bivalves (*Anadara* spp.), whereas the plume-shaped fine muddy bottoms off the Po River delta and the deeper muddy sand habitats host communities characterized by a lower shellfish density and abundance.

The study design has two major limitations related to the inclusion of a captive experiment: the absence of a control group, which is a powerful element to observe and isolate potential experiment-induced mortality (ICES, 2016), and the short duration of observation, which did not allow assessing asymptotic mortality (ICES, 2014). These limitations can introduce unverifiable sources of uncertainty if the captive experiment results are used to infer an absolute survival indicator. However, the results of the hazard model may be taken as measuring potential survival compared with a reference vitality class, i.e. the one in which specimens have the best liveability (in our case, class A). Clearly, potential survival values are likely to differ from long-term absolute survival and should not be used to apply for LO exemptions. Nonetheless, the approach does provide preliminary survival estimations in relation to major stressors in a given fishery, which are especially valuable when the available resources do not allow meeting all the requirements of a robust captive survival experiment.

According to aggregate data analysis, the mortality hazard increased from vitality class A through C, in line with the absolute survival results reported by other studies of flatfish species (Catchpole *et al.*, 2015; Randall *et al.*, 2017; van der Reijden *et al.*, 2017). Nevertheless, the scenario approach highlighted a significant relationship where the main drivers were high temperature and longer air exposure, whereas the scenarios where the drivers were high catch volume and low temperature did not yield a significant relationship (Table 4). This suggests that the catch weight might be a source of confusion because it can induce internal damage that may not be immediately apparent. Since catch stress can cause a hyperactivity condition (Donaldson *et al.*, 2013), fish suffering from internal damage might appear healthy at the time of sorting but die a few days later. A further SQA performed after a certain time (for instance before captive observation) might address the problem: the confirmation/revision of the first SQA would then be added to the survival model.

Scenario analysis indicated that sets of data-derived fishery-dependent conditions can produce different final relative survival estimates since the aggregate RS value of 22.9% involved a range from a *minimum* of 10.5% in unfavourable conditions (WRM-LAE) to a *maximum* of 33.4% in favourable conditions (CLD-LW). The analysis also revealed that stressor interaction can enhance potential discard survival since a shorter air exposure seems to be the key factor increasing RS in unfavourable warmer conditions (WRM-SAE) whereas lower catch weight plays the same role in colder ones (CLD-LW).

*Ad hoc* mitigation strategies based on the results of this case study should primarily take into consideration the environmental stressor (in this case temperature) and catch weight. Seasonal LO exemptions have been granted in the North Sea area based on similar results (EU, 2018a); in particular, the introduction of temperature-dependent limitations to towing duration could reduce catch weight and sorting time. Nevertheless, management measures based on environmental conditions are difficult to formulate and implement due to their seasonality and intrinsic variability. On the Italian side of the Adriatic a spatial measure (a trawling ban in late summer) already limits the catches of undersized specimens (Scarcella *et al.*, 2014). A side effect of this measure is a reduction in discards in part of the warm season.

Alternatively, mesh size limitations are (direct) measures to reduce the catch of juveniles of target species (Catchpole *et al.*, 2005) and to allow a larger number of individuals of non-target species (e.g. bivalves) to escape, thus also reducing catch weight. If fishing restrictions are not imposed in unfavourable temperature conditions, the best approach to maximize discard survival may be to act on handling practices by reducing air exposure duration (mimicking the WRM-SAE scenario). Considering the characteristics of GSA 17 and the common sole fishery, the handling practices envisaged by the EU (EU, 2018b), whereby discards are rejected “immediately in the area where they have been caught”, may provide a rule of thumb to improve survival irrespective of any other condition.

Altogether, the results of this work confirm that a general view of the system may not be the most accurate. The interactions of the effects of environmental and fishing dynamics described in the literature (Morfin *et al.*, 2017; van der Reijden *et al.*, 2017; Kraak *et al.*, 2019) suggest that the results observed in a specific context may not be amenable to generalization, even within a single fishery. In contrast, a scenario-based approach is considered very informative for management decisions (Cook *et al.*, 2019) because it provides an outlook of different hypothetical and realistic situations and quantitative thresholds. It is well known that solutions that involve high costs or changes to fishing practices are not easily accepted by fishers (Watson *et al.*, 2018). Since fishers’ involvement and commitment are critical for the successful adoption of all management measures, mitigation strategies based on multiple management solutions could perhaps be explored instead of a single measure. For instance, the European Commission has developed tailored measures for high survival exemptions in the North Sea, where multiple LO exemptions have been granted within a single Management Unit—for instance to boats targeting common sole in ICES division 4c—for certain vessel lengths, haul depths, and towing durations (EU, 2018a).

## Data availability statement

An open source software implementation of the methods described in this paper, together with experimental data, is available under a Creative Commons licence at https://github.com/EnricoNArmelloni/SOLEA (last accessed June 2020).

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