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Survival of undersized plaice (*Pleuronectes platessa*), sole (*Solea solea*), and dab (*Limanda limanda*) in North Sea pulse-trawl fisheries

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The European Commission landing obligation, including species-specific "high survival" exemptions, has established a need for accurate discard survival estimates. This study presents the first discard survival estimates on-board Dutch commercial pulse trawlers. During seven, six, and one fishing trip(s), respectively, undersized plaice (*Pleuronectes platessa*), sole (*Solea solea*), and dab (*Limanda limanda*) were collected, assessed for vitality and subsequently monitored up to 21 days. Uncorrected for any potential impacts from predation, tagging, research-related handling, or holding conditions overall survival for plaice ($n = 349$), sole ($n = 226$), and dab ($n = 187$) was assessed as 15% [95% *CI*: 11–19%], 29% [95% *CI*: 24–35%], and 16% [95% *CI*: 10–26%] respectively. Survival was mainly effected by water temperature and factors linked to the fishing vessel. Fish length was not found to affect survival. Catch processing time and haul duration affected plaice survival but not sole. Vitality index, which averages reflex impairment and external damage scores, correlated with survival and may be developed as a proxy for discard survival. Compared to tickler-chain beam trawlers, pulse trawlers showed relatively higher discard survival under fishing conditions pertinent to these studies.

Keywords: bottom trawling, discard mortality, pulse trawling, reflex impairment.

Introduction

Demersal fisheries for flatfish in the North Sea are characterized by catches of various target and bycatch species (Catchpole *et al.*, 2005; Gillis *et al.*, 2008). Main target species in these fisheries include sole (*Solea solea*) and plaice (*Pleuronectes platessa*), with undersized plaice and dab (*Limanda limanda*) being frequently discarded (Catchpole *et al.*, 2008). To curb the practice of discarding, the European Commission has implemented a discard ban or landing obligation (LO), beginning in 2015 for pelagic fisheries and including other fisheries and areas in Europe in subsequent years (EU, 2013). By 2019 the LO shall be in force for all quota-regulated species. Following this regulation, fishers are allowed to continue to discard species that, according to the best available scientific advice, have a high chance to survive when returned to sea (EU, 2013). This "high survival exemption", however, does not provide a definition of what level is regarded as "high".

The introduction of the LO and its "high survival" exemptions have increased the need for accurate discard survival estimates in

North Sea fisheries. Previous studies in the region have assessed survival of undersized plaice and sole in various beam-trawl fisheries. Commercial beam trawlers (with an engine power >221 kW) showed survival percentages of <10% for both plaice and sole after 84 h of observation (van Beek *et al.*, 1990). Similar fishing practices in the English Channel, but on larger plaice and sole, resulted in survival estimates of 22–48% (February) and 40–69% (May) for sole and 16–43% (February) and 42–71% (May) for plaice after 3 days monitoring (Revill *et al.*, 2013). The survival of these species caught with a vessel representative of smaller, coastal beam trawlers (so-called Eurocutters, with an engine power < =221 kW and fishing with 4.5 m beam trawls) during commercial haul durations of ∼90 min were found to be 48% for plaice and 14% for sole after 77 and 91 h monitoring, respectively (Depestele *et al.*, 2014b). Shorter haul durations (∼30 min) resulted in a survival estimate of 39.4% for plaice after 144 h observation (Kaiser and Spencer, 1995). A recent survival study of five trips onboard a commercial Eurocutter resulted in similar survival estimates of 50% for plaice after 14 days when caught in hauls with commercial representative durations, but in survival estimates of 75% when caught in hauls with short duration (< =20 min) (Uhlmann *et al.*, 2016a). Data on dab discard survival are very limited but the survival estimates were thought to be similar to those for plaice (Kaiser and Spencer, 1995; Depestele *et al.*, 2014a).

Owing to logistical and technical challenges, captive observation studies are labour-intensive and expensive to conduct. As an alternative, it has been proposed that health and vitality assessments can be used as survival proxies (Davis and Ottmar, 2006). Vitality is assessed based on status indicators (Benoît *et al.*, 2015). To utilize such vitality-based proxies, species-specific correlations between vitality and survival should be established first. Immediate flatfish survival has been linked to externally perceptible damage such as haemorrhaging (van Beek *et al.*, 1990; Kaiser and Spencer, 1995). However, non-visible negative trawling effects, such as disorientation, stress and internal injury, could decrease post-release survival as well. Therefore, the scoring of impaired "reflexes" is suggested in addition to scoring of external damage (Davis and Ottmar, 2006). Such reflexes are species-specific and refer to innate action patterns, for instance whether a (flat)fish is able to right itself when released upside down (ICES, 2014). An explorative study to identify appropriate reflexes for plaice and sole was completed in March 2014 onboard the RV Belgica (Depestele *et al.*, 2014a). For plaice caught in Belgium coastal beam trawls, a vitality index combining reflex scores and external damage assessments showed a strong correlation with survival (Uhlmann *et al.*, 2016a). However, a vitality index has not yet been developed and tested for plaice and sole in pulse-trawl fisheries.

In the Netherlands, demersal beam-trawl fisheries targeting sole have replaced traditional tickler-chain beam trawls with pulse trawls (Haasnoot *et al.*, 2014). Pulse trawls use electrical stimulation to evoke a cramp reaction in demersal fishes, whereupon fish leave the seabed and are retained by the passing trawl (Soetaert *et al.*, 2015). Due to the replacement of heavy tickler chains by lighter electrodes and lower towing speed (typically 4.5–5 knots instead of 6–7), pulse trawling reduces fuel consumption (Taal and Hoefnagel, 2010), benthic impact (Depestele *et al.*, 2015), and catch of benthos and undersized fish (van Marlen *et al.*, 2014; K. J. van der Reijden, pers. comm.). In addition, the electrical stimulation specifically evokes a strong reaction in sole, resulting in higher catchability than tickler-chain beam trawls (Soetaert *et al.*, 2015).

Discard survival studies in pulse-trawl fisheries are lacking. One study, by Uhlmann *et al.* (2016a) assessed the vitality of undersized plaice and sole but not their survival (van Marlen *et al.*, 2005; Uhlmann *et al.*, 2016a). Our paper presents the first results of survival monitoring of undersized plaice, sole and dab discarded from commercial pulse-trawl fisheries, taking in account the guidelines and best practices presented by the Workshop on Methods for Estimating Discard Survival (WKMEDS) of the International Council for the Exploration of the Sea (ICES). This study also tested the potential of four status indicators for their correlation with mortality, to serve as proxies for survival, and explored which factors are most likely to affect discard survival.

Material and methods

All experiments were conducted during eight trips on-board two commercial pulse trawlers operating under conventional conditions in the southern North Sea (Table 1; Figure 1). During three trips, two modified hauls were performed with a shortened duration (∼60 min) to test for the effect of haul duration on survival. Plaice and sole survival were estimated during seven and six trips, respectively, whereas dab survival was estimated during one trip (Table 2). Operational conditions for each haul such as date and average towing speed, time and position at the start and end of each haul, and environmental conditions such as average fishing depth and water temperature were recorded by the skipper.

Equipment

During each trip, three custom-built flow-through monitoring units were installed on-board the vessels. Each monitoring unit consisted of 16 monitoring containers (24 l; 60 cm L × 40 cm W × 12 cm H), with individual water in- and out-flow (∼1.5 l min^{-1}) and space for 5 flatfish (B. van Marlen, pers. comm.). During each trip undersized flatfish from the catch were placed in each monitoring container. At the conclusion of each trip the monitoring units were road-transported to the laboratory during a 1 h-drive in a refrigerated truck with recirculating seawater and individual air supply. In the laboratory, the monitoring containers were stacked in racks and connected to a continuous water flow system, using continuously pumped filtered water from the Oosterschelde. The fish were monitored and fed ragworm (*Nereis virens*) *ad libitum* every 24 h.

Sampling protocol

In each sampled haul, 40 undersized fish were collected per species. Twenty undersized fish were sequentially collected at the start and at the end of the catch-sorting process, because processing time is likely to affect discard survival (Benoît *et al.*, 2013), and then placed in a 105 l holding container with continuously refreshed surface sea water (20 l min^{-1}) to maintain dissolved oxygen levels. Five fish were then randomly taken from the holding container and assessed for vitality. Live fish were measured for total length (TL; in cm below), tagged, and then stored in a 24 l monitoring container. If a dead fish (death was defined as non-breathing and non-responsive for at least 10 s of observation, including grabbing its tail as external stimuli) was encountered upon vitality assessment, external damage and TL were recorded. Then, it was replaced by another fish that was randomly sampled from the holding container until a total of five fish were placed in

Table 1. Vessel and gear specifics.

Vessel	ID	GO23	GO31
	Name	"Cornelis Jannetje"	"Morgenster"
	Engine power (kW)	1430	1125
	Tonnage (GT)	366	495
	Length (m)	39	42
	Gear	Sumwing pulse	Sumwing pulse
	Number of gears	2	2
	Fishing speed (kn)	4.8	4.8
Beam (wing)	Width (m)	12	12
	Length (m)	1.1	1.07
	Total weight (kg in air)	140	250
False ground rope	Type	Rubber discs	Rubber discs
	Length (m)	11	12
	Diameter (mm)	120	180
	Total weight (kg in air)	140	250
Electrodes	Number	24	25
	Type	HFK	HFK
	Total length (m)	7.2	6.7
	Distance between electrodes (m)	0.425	0.425
	Length electrodes on seabed (pulse field) (m)	3.2	3.2
Conductor elements	Number	10	10
	Diameter (mm)	28	28
	Length (mm)	130	130
	Distance between elements (mm)	210	210
Pulse	Power (kW/m)	5.3	5.2
	Width (μs)	390	260
	Frequency	45	80
	Peak voltage over electrode (Vpeak)	50	50
	Maximum exposure to pulse field (s)	1.3	1.3
Trawl	Total length (m)	30	23
	Mesh size cod-end (mm)	80	80
	Twine cod-end	Double knotted	Double knotted
	Twine thickness (mm)	3	4

the monitoring container or no fish were left in the holding container. Due to differences in sorting process and vitality assessment durations between hauls, each sampled fish spent a different amount of time in the holding container, resulting in differences in so-called "recovery time".

Vitality assessment included the scoring of seven reflex impairments and the presence/absence of six external damage types

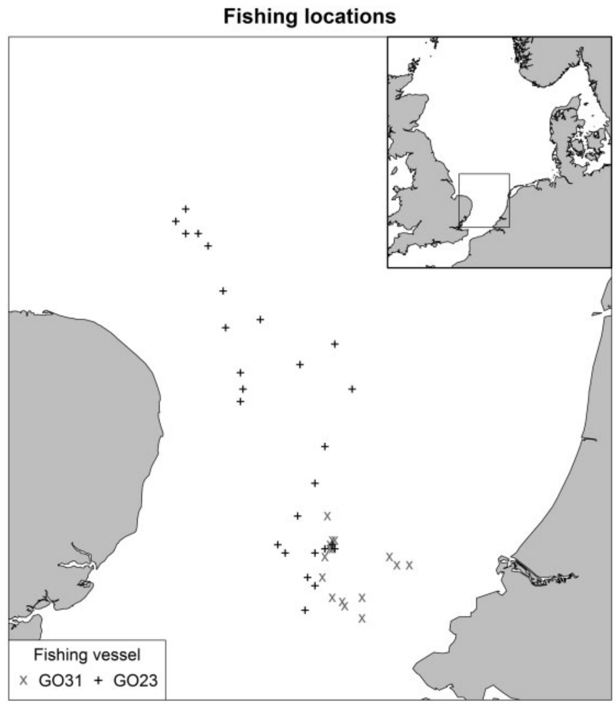

Figure 1. Geographical positions of sampled hauls of participating commercial Dutch pulse trawl vessels in the Southern North Sea between the Netherlands and the United Kingdom.

(Table 3). Additionally, fishes were classified in four vitality classes [A (lively) to D (lethargic)], according to the protocol of van Beek *et al.* (1990). This resulted in four possible status indicators: vitality class; reflex impairment score (ratio of impaired reflexes/total reflexes tested); external damage score (ratio of present damage/total damage tested); and a combined vitality score (impaired reflexes + present damage/[total reflexes tested + total damage]). All vitality assessments were performed by three trained observers, to minimize observer bias. However, only one observer was present on-board per trip.

Tagging was performed to ensure individual tracking of each fish, with Trovan® Unique glass transponders (type ID100) being injected subcutaneously in the tissue, just behind the head using the injector IID100E. The Trovan® pocket reader LID573 read out the serial tag number after injection.

Control fish

Control fish were used to account for potential effects from tagging, handling, and transportation as part of the experimental holding process. These fish were mainly caught by a small shrimp trawler (~123 kW) using a 20 mm mesh beam trawl towed at 2–3 knots for ~15 min. Control fish were also collected by both participating pulse trawlers from short hauls (~30 min) during winter, when fish had migrated offshore and were out of reach by the shrimp trawler. Visual inspection selected the least damaged fish, which were stored in 600 l aerated containers with a continuous seawater supply, and then driven to the laboratory within a day. After at least 17 days of acclimatization until any mortality had levelled off, control fish were randomly selected before an experimental fishing trip, taken on-board the pulse trawler, and stored in 600 l aerated holding containers with continuous seawater supply until treatment. After random collection of five individuals from the holding container, control fish were exposed to similar handling as fish from the catch, including vitality assessment, tagging and transfer to the monitoring containers.

Monitoring

Survival monitoring started directly after placing the treatment fish in the 24 l monitoring containers. The fish were monitored every 12 h for the first few days on-board the vessels and then daily at the laboratory. During monitoring, dissolved oxygen levels (mg l^{-1}), water flow (l min^{-1}), and water temperature (°C) were checked; any food remains and dead fish were removed. Standard procedure was to first observe the fish through the transparent lid of the tank and subsequently measure water quality. Seemingly lethargic fish were assessed for their tail grab reflex response, and both the mouth and operculum were observed for movements for 10 s to confirm status. If no reaction was observed, the fish was removed from the monitoring container. Monitoring continued for at least 21 days.

Table 2. Overview of sea trips.

Trip	Vessel	Year	Week	Start date	End date	Species
1	GO31	2014	47	17/11/14	21/11/14	SOL, PLE
2	GO23	2015	11	09/03/15	13/03/15	PLE, DAB
3	GO31	2015	15	06/04/15	10/04/15	SOL
4	GO31	2015	17	20/04/15	24/04/15	SOL, PLE
5	GO23	2015	24	08/06/15	12/06/15	SOL, PLE
6	GO31	2015	28	06/07/15	10/07/15	SOL, PLE
7	GO23	2015	31	27/07/15	31/07/15	SOL, PLE
8	GO23	2015	39	21/09/15	25/09/15	PLE

SOL, sole; PLE, plaice; DAB, dab.

Analysis

Observed survival

Some fish were dead at the beginning of the vitality assessment inside the 105 l holding container. As these fish could have died in the pulse-trawl, during catch processing, or while being held captive inside the holding container, these fish were recorded dead at time zero (Defined as immediate mortality; these fish were left censored). The overall survival for treatment fish and the control group was estimated using the non-parametric Kaplan–Meier estimator (Kaplan and Meier, 1958). Suppose k distinct death times are observed: $t_1 < t_2 < \ldots < t_k$ during follow ups, the estimated survival probability at time t is calculated as:

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

where n_i is the number of fish at risk at the beginning of time t_i and d_i is the number of fish that died at time t_i. In case fish

Table 3. Description of criteria to score vitality status.

Vitality class	
Class	**Description**
A	Fish lively, no visible signs of loss of scales or mucus layer.
B	Fish less lively, minor lesions and some scales missing, mucus layer affected up to 20%, some point haemorrhaging on the blind side.
C	Fish lethargic, intermediate lesions and some patches without scales, mucus layer affected up to 50%, several point haemorrhaging on the blind side.
D	Fish lethargic or dead, clear head haemorrhaging, major lesions and patches without scales, mucus layer affected for more than 50% on the blind side with significant (point) haemorrhageing.
External damage scores	
Damage	**Description (1= present; 0=absent).**
Fin	Fins are damaged.
>50%	Damage to skin surface, scale or mucus layer at more than 50% of the dorsal body surface.
Head haemorrhage	Presence of a haemorrhage in the head of the fish.
Hypodermic haemorrhages	Presence of a hypodermic haemorrhage.
Intestines	Intestines are protruding or are visible through damaged body tissue of the fish.
Wound	Presence of a wound, such that flesh is visible.
Reflex impairment scores	
Reflex	**Description (1= impaired; no (clear) response within 5 s of observation; 0= unimpaired; obvious response within 5 s).**
Body flex	Fish is held on the palm of a flat hand with its ventral side up in air. Fish actively tries to move head and tail towards each other or wriggle out of the hand.
Righting	Fish is held on the fingers of two hands with the dorsal side touching the water surface. Fish actively rights itself under water when released.
Evasion	Fish is held underwater in an upright position by supporting its ventral side with the fingers and its dorsal side with the thumbs. Then, the thumbs are lifted and the fish is gently released. Fish actively swims away.
Stabilize	Untouched fish tries to find a stable position flat on the bottom by rhythmic and swift movement of the fins and/or body.
Tail grab	Fish is gently grabbed by the tailfin between thumb and index finger. Fish actively struggles free and swims away.
Head-complex	Fish moves its operculum or mouth during 5 s of observation, while laying undisturbed under water.

Categories of vitality classes were defined following van Beek *et al.* (1990).

dropped out of the study due to other causes (e.g. infections) at time t_i, n_i is calculated as the number of fish survived time t_{i-1} minus the number of these fish (right censored). Survival of treatment fish and control fish was compared using a log-rank test.

Survival indicators

The four status indicators vitality class (categorical), reflex impairment index, external damage index, and vitality index were fitted separately via a mixed effect cox proportional hazard model to determine which indicator produced the highest cox proportional hazard ratio (coxme; Therneau and Grambsch, 2000). The general expression of an estimated hazard function at time t is:

$$\hat{h}(t) = h_0(t)\exp(X\beta + Zb), \quad (2)$$

$$b \sim N(0, \Sigma) .$$

The hazard function $\hat{h}(t)$ is defined as the conditional probability of mortality at time t, given that it has survived until t and $h_0(t)$ is the baseline hazard. Vector β is the fixed effect, with design matrix X derived from the covariates (in this case indicator type only). Vector b is the random effect, with design matrix Z derived from the haul index. This simple random intercept b accounts for haul-specific factors, such as substrate type and stone presence in the catch, which are assumed to follow a normal distribution with a local variance between hauls (Σ). A Cox model is semi-parametric because the baseline hazard is not dependent on the covariates. Instead, it assumes that the hazard in one group is a constant proportion (i.e. hazard ratio) of the hazard in the other group over time. Model parameters were estimated through integrated partial maximum likelihood. Since the purpose is to select the best predictor for survival, the best indicator type was then selected with the lowest akaike information criterion (AIC).

Ideally, potential observer bias should be determined by including observer as random factor in the coxme model. Due to the experimental set-up, however, all vitality assessments per trip were scored by one observer. It is therefore impossible to correctly test whether observed differences are caused by observer bias or between trip differences. As we did observe large variation in survival and damage between trips, we decided to not include observer as covariate but instead include haul as a nested factor to correct for differences between trips and between hauls.

Factors influencing survival

Based on previous studies and some practical constrains of this study, we hypothesized that water temperature (°C), water depth (m), total processing time (min), recovery time (min), fish length (cm), and fishing vessel (GO23 vs. GO31) were most likely associated with discard survival. Water depth and temperature were highly correlated for sole (Pearson correlation coefficient: 0.84 for sole). We expected water temperature and not pressure (depth) to have the greatest physical impact on treatment fish, and therefore decided to exclude water depth as an explanatory factor. For water temperature, the measurements were aggregated in two clusters; ones that were around 13–14 °C and others that were 8–9 °C. No intermediate measures have been made and hence, we categorized the measurements in two categorical classes. Fishing vessel also showed correlation with water temperature, however, fishing vessel was kept as an explanatory factor because it captured additional operational differences such as fishing location, trawling speed, and fish processing practices. Due to the limited dataset of dab, the analysis was only performed for plaice ($n = 329$) and sole ($n = 226$).

A coxme model [see (2)] was then applied based on these five covariates (i.e. fixed effects) and the haul index as random effect. Since the purpose of this analysis was to find the most plausible explanatory factors for survival, rather than finding the best prediction model, we selected the best explanatory model based on the consideration of the model fitting (minimum AIC), the collinearity of the covariates, and the plausible biological effects. This objective would support the inclusion of fishing vessel as a random effect. However, since only two vessels participated in this study, we feel that fleet variation cannot be estimated appropriately. Individual vessel effects are hence estimated using fishing vessel as a fixed effect. The estimated hazard ratio is presented and the p-value (null hypothesis that the hazard ratio equals 1) was calculated from a Wald test.

Additionally, haul duration (in min) was considered an important explanatory factor of discard survival. However, during commercial practice all hauls had a similar duration. In three trips, two short hauls (∼60 min) were conducted and survival was compared to survival of standard commercial hauls from these trips using a coxme model (2). The fixed effects are then trip index and haul duration (60–70 vs 100–130 min).

All data analyses were conducted using the open source programming language R (R Development Core Team, 2004), and the R-packages "survival" and "coxme" (Therneau and Grambsch, 2000; Jackson, 2016).

Results

Observed survival

During seven, six, and one fishing trip(s), respectively, 349, 226, and 187 discarded plaice (22.2 ± 3.6 cm TL, mean ± *SD*), sole (21.6 ± 2.5 cm TL), and dab (19.8 ± 2.3 cm TL) were collected from conventional pulse-trawl hauls, assessed and monitored for survival. Overall survival was defined as the asymptotic percentage of fish being alive. Using the non-parametric Kaplan–Meier estimator, the survival percentage at $t = 25$ days was estimated. For plaice, average survival percentage was 14.6% (95% *CI*: 11.3–19.0%; Figure 2a). Sole showed higher overall survival, with an average of 29.1% (95% *CI*: 24.1–35.2%; Figure 2b). Dab had an overall survival of 15.9% (95% *CI*: 9.8–25.7%; Figure 2c) for the one sampled trip. Treatment fish of all species showed most mortality (>95%) within the first week followed by a stabilization in the second week (Figure 2a–c). In the first week, all control fish showed significantly higher survival than treatment fish (log-rank test; $p < 0.01$; Figure 2a–c) but for plaice and dab, some mortality among control fish was observed from the second monitoring week onwards (Figure 2a and c), which in the case of plaice resulted in ∼50% survival (Figure 2a).

Status indicators

Survival was correlated with all four status indicators among both plaice ($n = 349$) and sole ($n = 226$). Dab was not included in this analysis due to the low sampling size. The vitality index (a combination of reflex impairment and external damage) predicted survival probability the best for both plaice (ΔAIC = 316 compared to ΔAIC = 273 for the reflex impairment index, ΔAIC = 238 for the vitality class, and ΔAIC = 192 for the external damage index) and sole (ΔAIC = 165 compared to ΔAIC = 160

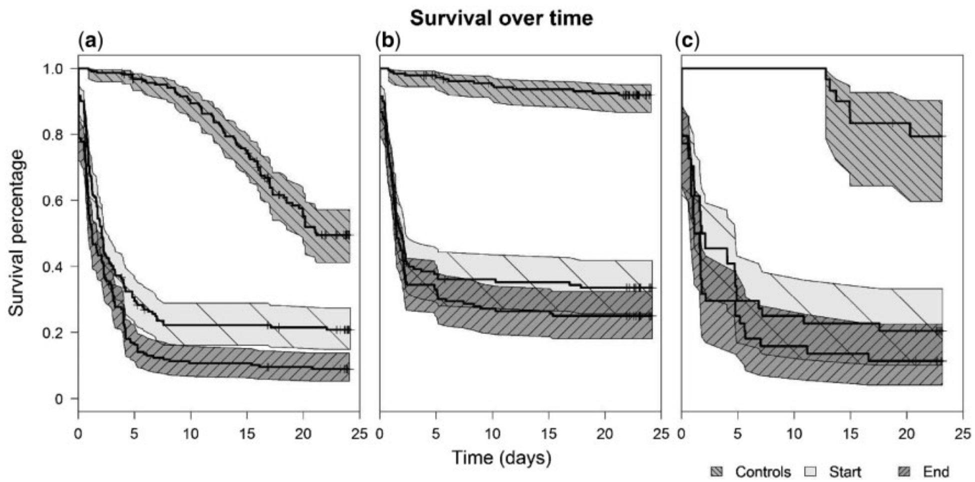

Figure 2. Non-parametric Kaplan–Meier survival probability estimates over days of monitoring of plaice (a), sole (b), and dab (c) per collection treatment (being picked off the sorting conveyor at the start or end of the sorting process) and controls.

for the reflex impairment index, ΔAIC = 157 for the vitality class, and ΔAIC = 79 for the external damage index). However, the commonly used vitality class showed a significant correlation with survival, indicating that results of the current study can be compared to previous studies, under the assumption of absent observer bias. Among all three species, the least number of individuals was scored as class "A". Sole and plaice were mainly classified as classes "B" and "C", respectively, while dab was scored mainly as class "D" (Table 4).

Factors influencing survival

Two models were selected for plaice with comparable low AIC scores, and biologically sound and consistent estimates; one including surface seawater temperature and catch processing time, while the second adds fishing vessel as explanatory variable (Table 5). In both models, water temperature had a significant effect ($p < 0.001$), but some of the observed variance can be explained by both catch processing time and fishing vessel. A significantly greater proportion of plaice survived when caught in shorter compared to conventional hauls ($n = 150$, mixed effect cox proportional hazard model coefficient ± SE = 0.528 ± 0.290; p-value= 0.028). Fish length and the so-called recovery time did not correlate with survival.

Due to the high collinearity between water temperature and fishing vessel for sole (Table 2), these factors could not be included in the same model. The most parsimonious model included both factors individually (Table 5), with strong differences between the fishing vessels ($p < 0.001$) and a negative effect of water temperature on survival probability ($p = 0.025$). No effect was found for haul duration ($n = 229$, mixed effect cox proportional hazard model coefficient ± SE = 0.770 ± 0.222; p-value= 0.240), recovery time, fish length, or processing time.

Table 4. Proportional contribution of each vitality class to total observations per trip.

Trip	Plaice				Sole				Dab			
	A	B	C	D	A	B	C	D	A	B	C	D
1	25	35	35	5	30	50	20	0	–	–	–	–
2	3	30	33	34	–	–	–	–	8	22	33	38
3	–	–	–	–	8	49	31	13	–	–	–	–
4	2	37	54	8	10	48	24	19	–	–	–	–
5	4	26	37	33	2	40	33	24	–	–	–	–
6	2	42	22	32	9	53	22	16	–	–	–	–
7	0	3	22	74	2	23	19	56	–	–	–	–
8	2	19	36	43	–	–	–	–	–	–	–	–
AV:	**5**	**27**	**34**	**33**	**10**	**44**	**25**	**21**	**8**	**22**	**33**	**38**

Discussion

This is the first study to quantify survival of undersized plaice, sole, and dab discarded from pulse-trawl fisheries, and the resulted in average survival estimates of 15%, 29%, and 16%, respectively. These estimates represent the percentage of alive fish after mortalities have ceased to occur over several days (i.e. stabilization of the survival to an asymptote). These estimates do not include potential post-release predation, which importance is demonstrated for sea birds (Garthe *et al.*, 1996), but remains unknown for other species (Raby *et al.*, 2014). The presented survival estimates could therefore be an overestimation of overall survival. Conversely, possible tagging, research-related handling, and holding effects are not corrected for, and as such, the presented average survival estimates may be an underestimation of overall survival.

Mortality related to tagging, research-related handling, and holding conditions is likely to have affected our results, because some control fish died. This may have been caused by being tagged, because the insertion of a tag creates an additional injury. However, tagging effects are thought to be negligible, at this methodology is applied in many studies with none to very limited observed mortality (e.g. Huusko *et al.*, 2016). Additionally, control fish may not have been representative of the treatment fish due to the acquisition process pre-selecting for the least damaged survivors. Moreover, all control fish were subjected to stressors not experienced by treatment fish, because of two additional transports and on-board storage until usage in the experiment.

The majority of treatment fish died within in the first 7 days (>95%), while control fish died from the second monitoring week onwards. This distinct pattern suggests distinct causalities for the observed mortalities, with mainly fisheries-induced

Table 5. Results of the best fitted mixed effects cox proportional hazard models for plaice ($n = 329$) and sole ($n = 246$), based on minimum AIC.

Model	Factor	Hazard ratio = exp (coefficient)	SE (coefficient)	*p*-value
Plaice model 1	Water temperature (8–9 °C vs. 13–14 °C)	0.297	0.330	<0.001[a]
	Total processing time (10 min)	1.275	0.140	0.082
Plaice model 2	Water temperature (8–9 °C vs. 13–14 °C)	0.337	0.330	0.001[a]
	Total processing time (10 min)	1.267	0.139	0.089
	Vessel (GO31 vs. GO23)	0.618	0.347	0.170
Sole model 1	Vessel (GO31 vs. GO23)	0.320	0.302	<0.001[a]
Sole model 2	Water temperature (8–9 °C vs. 13–14 °C)	0.420	0.387	0.025[a]

[a]indicates statistically significant at a level of 0.05.

mortality in treatment fish vs. mortality associated with research-related handling and holding conditions among control fish. Therefore, in combination with the potential unrepresentativeness and additional stressors to control fish and in line with the ICES WKMEDS guidelines (ICES, 2014), we decided to not correct treatment survival estimates for control mortality. We emphasize that our survival estimates may be underestimates by being confounded from tagging, research-related handling, and holding conditions effects.

In this study, four status indicators were tested to identify potential survival proxies for plaice and sole in pulse-trawl fisheries. All status indicators were strongly correlated with survival. Vitality index showed the highest significant correlation with survival. Strong correlations between a similar index and survival were found for plaice caught by beam trawls in Belgium (Uhlmann *et al.*, 2016a) and for various roundfish species (Davis and Ottmar, 2006; Raby *et al.*, 2012). Survival of sole in "Eurocutter" and traditional beam trawls correlated well with external damage (Depestele *et al.*, 2014b), while laboratory studies showed that survival of other flatfish species was strongly correlated with a reflex index (Davis and Ottmar, 2006; Barkley and Cadrin, 2012). The observed relationship between vitality and survival potentially could stimulate additional vitality data collection as part of regular monitoring campaigns (as done by Benoît *et al.*, 2015) to assess fleet-wide discard survival by using vitality assessments as a proxy for survival. This approach, however, is only appropriate if conditions are similar between vitality assessment collection and the vitality-survival relation establishment study (Davis and Ottmar, 2006). Moreover, vitality assessment studies cannot be used to determine discard survival under conditions that deviate from the conditions in which the vitality-survival relation was established. In this study, plaice and sole with the highest vitality index scores showed 54% and 72% survival, respectively. This suggests that the current vitality assessments might not incorporated all factors affecting survival, and as such are not appropriate to assess survival by themselves. Possibly, very high stress levels and internal damage might not be visible or expressed during vitality assessments.

Operational, environmental, and biological factors are believed to affect discard survival, for instance fishing gear type and location (depth, bottom type), haul duration, catch composition and weight, salinity, water temperature, fish length, fish condition, species characteristics, and processing time (Kelle, 1976; van Beek *et al.*, 1990; Kaiser and Spencer, 1995; Harris and Ulmestrand, 2004; Depestele *et al.*, 2014b; Uhlmann *et al.*, 2016a;). Additionally, we expected that vessel-specific details such as gear configuration, heaving speed and catch sorting processes could affect discard survival. Therefore, we included the factor vessel, although one would expect that vessel itself has no (negative) physical effect on the discarded fish. As only two vessels participated, both with distinct fishing grounds, the factor vessel incorporates fishing location as well.

Our study shows that both water temperature and fishing vessel affect both plaice and sole survival, with reduced survival in the higher seawater temperature class 13–14 °C. This is congruent with earlier findings (van Beek *et al.*, 1990 [9–18 °C]; Davis, 2002 [5–16 °C]), although the effect of water temperature is not always as strong as we found (Uhlmann *et al.*, 2016a [5–17 °C]). It is unclear, however, whether higher temperature *per se* or thermoclines during the hauling process cumulatively stressed treatment fish. Elevated temperatures do exacerbate physiological responses towards commercial fishing capture stress (Davis, 2002; Broadhurst *et al.*, 2006; Gale *et al.*, 2011, 2013), due to an increase of the fish's metabolic rate and a decrease of dissolved oxygen, resulting in a rapid depletion of energy reserves (Pörtner and Knust, 2007; Gale *et al.*, 2013). Our results confirm that stress experienced during warmer (summer) as opposed to cooler (winter) temperatures contributes to post-release mortality (van Beek *et al.*, 1990; Giomi *et al.*, 2008). In addition to absolute temperatures, abrupt temperature differences may impose additional stress (Galloway and Kieffer, 2003). By hauling fish from deeper, colder waters to relatively warm surface waters, these thermoclines can be encountered (Catchpole *et al.*, 2015). Third, seawater temperature may correlate with season and thus associate with pre- and post-spawning condition of fish. During and directly after the spawning season, female fish are generally in a poorer condition than during the rest of the year, which may make them more vulnerable to trawling effects (Ortega-Salas, 1980). Revill *et al.* (2013) showed large seasonal differences in plaice survival with poor survival of spawning plaice. Similar trends were not observed for sole, although sampling period did cover sole spawning period. This suggests a species-specific capability to cope with temperature stress. The inclusion of a body condition measure (such as Fulton's *k*: the ratio between body mass and TL) has shown some value in linking seasonal fluctuations of body condition with survival estimates of plaice (Uhlmann *et al.*, 2016b). Finally, due to the collinearity between water temperature and depth and the assumed larger impact of water temperature, we did not take encountered pressure differences into account in this study. However, especially during the hauling process from deeper waters, next to thermocline effects, barotrauma effects may become important as well (Davis, 2002). Although flatfish are thought to be affected less by pressure differences than fish with a swim bladder, pressure differences potentially have impacted the survival estimates of our discards.

Survival differed between the two fishing vessels, for both plaice and sole. For sole, fishing vessel correlated with seawater temperature, what therefore may have confounded the vessel effect. However, we hypothesize that the observed survival differences are most likely explained by the different fishing locations of both vessels, with one vessel fishing at a more pebbly substrate than the other. To correctly test this hypothesis, a trawling experiment should be conducted, with equal fishing practice at different substrates under further similar conditions.

Additionally, haul duration and catch processing time as practiced under commercial conditions negatively affected plaice survival, but not sole. The capability of sole to cope with air exposure was already shown by Uhlmann *et al.* (2016a). However, this would explain the effects of catch processing time and not those of haul duration. Haul duration physically imposes a stressor to fish by an enhanced probability of net-scrubbing, being pressed against meshes, and being subjected to abrasion by other fish, invertebrates or sediment caught up inside the net (van Beek *et al.*, 1990; Kaiser and Spencer, 1995; Davis, 2002). Moreover, longer haul durations are correlated with higher catch volumes (Somerton *et al.*, 2002), which are assumed to cause damage to the fish during towing and hauling (Broadhurst *et al.*, 2009). Why sole is better capable to cope with the conditions of longer haul durations remains unknown?

Fish length did not affect survival, although in general it is observed that small fish show increased mortality (Davis, 2002; Revill *et al.*, 2013; Uhlmann *et al.*, 2016a). Uhlmann *et al.* (2016a) for instance, observed a strong positive relationship between discarded plaice size and survival. Why we did not see a similar relationship may be an effect of length selection (solely undersized fish were studied). Average fish length in this study was smaller than plaice and sole studied by Revill *et al.* (2013), but similar to Uhlmann *et al*, (2016a).

Under commercial pulse-trawl conditions, the most recent study by Uhlmann *et al.* (2016a) compared vitality of plaice and sole caught-and-discarded from pulse vs. conventional tickler-chain beam trawls, but did not monitor survival or released fish (Uhlmann *et al.*, 2016a). In addition, two explorative studies were performed in the Netherlands (van Marlen *et al.*, 2005, 2013). All three studies suggest that pulse trawls result in more vital discards than traditional beam trawls and hence, have higher discard survival, assuming consistent vitality assessments and a similar correlation between vitality and survival. A historic study conducted on-board conventional beam trawlers fishing in a comparable part of the North Sea, using similar sized fishing vessels, and operating under similar conditions (commercial haul duration of 2 h and comparable water temperatures) resulted in estimated survival of <10% (van Beek *et al.*, 1990). This study used a different methodological set-up for the captive observations and did not monitor to asymptote. However, the majority of the undersized plaice and sole were classified as "D" for their vitality class, whereas most plaice and sole in our study were classified as "C" and "B", respectively. This is congruent with the three studies aforementioned, showing more vital and less impaired fish in the pulse trawl compared to the traditional beam trawl. Recently, a similar discard survival study was performed in beam-trawl fisheries in the southern North Sea (Uhlmann *et al.*, 2016b). This research included two trips on-board a Belgian commercial sumwing-beam trawler (~1491 kW). Although limited in its replicates and performed in a summer period of high water temperature (~16 °C), the results showed lower (<5%) plaice discard survival than presented for the pulse-trawl fisheries in this paper. However, a more detailed analysis of these data in comparison with data from trips six and seven which fall into the same summer period is yet to be done.

All comparisons between pulse- and beam-trawl survival studies (both recent and historical studies) performed under similar conditions suggest higher discard vitality in the pulse trawl. However, these comparisons are made with only small numbers of observations and should be interpreted with caution as historic fishing practice (~25 years ago) might not be representative of today's fisheries. Survival in beam trawlers may have changed over time, as gear configurations are expected to have changed as well (Eigaard *et al.*, 2014). Plaice and sole survival in present-day English Channel beam trawlers, for instance, showed higher survival estimates than the estimates presented here, although some caution should be incorporated because of a different study area, a shorter monitoring period and larger fish (Revill *et al.*, 2013). Comparative fishing experiments should be performed to assess survival differences between pulse and traditional beam trawls. In addition, almost all survival studies so far have identified substantial discard mortality. Although the pulse trawl may result in higher discard survival estimates than the traditional beam trawl, one could argue that having no discards at all would be more beneficial for the fish populations. Selectivity studies, which avoid discards to be caught in the first place, should therefore receive research priority.

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