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A Transdisciplinary Approach Towards Studying Direct Mortality Among Demersal Fish and Benthic Invertebrates in the Wake of Pulse Trawling

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Between 2009 and 2020, beam trawlers in the North Sea switched to electrical stimulation to target sole (*Solea solea)*. The transition to pulse trawling raised widespread concern about possible adverse effects of electrical stimulation on marine organisms. Environmental NGO's and small scale fishers claimed that it would electrocute marine life and create a 'graveyard' in the wake of pulse trawlers. This paper uses realistic field experiments to investigate the 'graveyard' hypothesis. In cooperation with fishers, a field experiment was designed where we simultaneously sampled marine organisms in the wake of pulse trawlers and in untrawled control areas. The impact was quantified by estimating the direct mortality among three dominant fish species and four dominant invertebrate species. In total, nine experimental tows were conducted in two years. Direct mortality among fish and invertebrates was low (0-10%) and did not differ between the pulse trawl track and the untrawled controls. Equally, no impact of the pulse trawl was found on external damages and vitality scores. The limited effects observed are likely due to the mechanical impact of the pulse and the sampling gear. The results of experiment do not support the claim that pulse trawling results in mass mortality among marine organisms in the trawl track. Throughout the research period, the concerns of small-scale fishers on pulse fishing shifted from being focused on biological effects to political and managerial issues. This can partly be attributed to the engagement in and the results of our research and has increased its credibility and salience. By integrating fishers' knowledge and examining their perceptions through transdisciplinary research, we were able to show the importance of untangling the intricate relation between perceived knowledge gaps and political or management related concerns.

Keywords: fisheries, impact, bottom trawling effects, mortality, Fisher's knowledge, Electrotrawling

INTRODUCTION

The Dutch beam trawl fishery in the North Sea is a mixed fishery that targets Dover sole (*Solea solea*) and plaice (*Pleuronectes* platessa) with other species as valuable bycatches (Gillis et al., 2008). The beam trawls are equipped with tickler chains to mechanically chase flatfish from the seabed into the net. In the North Eastern Atlantic, the beam trawl fishery is considered to be among the fishing gears with the largest ecological impact on the benthic ecosystem because the tickler chains penetrate the sediment and disturb the top layer of the sea bed (Hiddink et al., 2017; Rijnsdorp et al., 2020b). The relatively small codend mesh size required to retain the slender sole results in large bycatches of undersized plaice (*Pleuronectes platessa*) and other fish species (Uhlmann et al., 2014; Rijnsdorp et al., 2020a *submitted*). The relatively high towing speed results in a high fuel consumption (Poos et al., 2013).

Between 2009 and 2021, part of beam trawl fleet targeting sole was temporarily allowed to switch to electrical stimulation with pulse trawls to explore the possible reduction of the adverse impact of conventional beam trawls on the ecosystem (Van Marlen et al., 2014; Haasnoot et al., 2016). Vessels used a pulsed bipolar current (PBC) that causes a cramp response that immobilises the fish and facilitates their catch (Van Stralen, 2005; Soetaert et al., 2015a; Soetaert et al., 2019; Rijnsdorp et al., 2020a, *submitted*). Beam trawl fishers were eager to switch to pulse trawling, as the pulse trawls proved to be robust and reliable, and because the gear was more efficient to catch sole at a lower speed and lower fuel consumption (Poos et al., 2020; Turenhout et al., 2016; Soetaert et al., 2015a). The Dutch government supported the transition by funding research projects and by negotiating the extension of the number of pulse licenses from 22 in 2009 to 84 in 2014 (Haasnoot et al., 2016).

The increase in pulse licenses was heavily criticized (Haasnoot et al., 2016; Le Manach et al., 2019; Kraan et al., 2020) and fueled the already existing concerns about the adverse effects on marine life and the consequences of the more efficient gear for other fishers (Stokstad, 2018; Quirijns et al., 2018). Pulse trawling was thought to electrocute marine life (Bloom, 2018). Recreational and small-scale fisherman from England, Belgium, France and Netherlands for instance claimed that such exposure causes direct mass mortality among fish and benthic invertebrates, resulting in a 'graveyard' in the wakes of pulse trawlers (Bloom, 2018). The available scientific knowledge did not support these claims. In particular, laboratory experiments did not find an increased mortality rate among marine organisms exposed to the electric pulse used in the fishery for sole (Smaal and Brummelhuis, 2005; Soetaert et al., 2015b; Soetaert et al., 2016a; Soetaert et al., 2016b; Soetaert et al., 2018; de Haan et al., 2009; de Haan et al., 2015), whilst field studies showed that over 90% of undersized plaice, common sole, turbot, brill and thornback ray caught in a commercial pulse trawl is alive when landed on deck (Schram and Molenaar, 2018, *submitted*). The only adverse effect of electrical stimulation shown by laboratory and field studies is the occurrence of spinal-injuries in cod (Van Marlen et al., 2014; De Haan et al., 2016; Soetaert et al., 2016a; Soetaert et al., 2016b). However, direct mortality in the wake of pulse trawlers was never studied under realistic field conditions.

Following the growth of the number of pulse licenses, the Dutch government funded additional research projects to fill knowledge gaps on the effects of electrical stimulation on marine organisms and organized a series of International Pulse Dialogue Meetings (Steins et al., 2017; Kraan and Schadeberg, 2018). In these meetings, aimed to discuss the results of the ongoing scientific research and the concerns with stakeholders and other interest groups, small-scale fishers reiterated the need to study the 'graveyard' question and expressed their interest to become involved in the research (Quirijns et al., 2018).

In this paper we report on a study of the direct mortality among demersal fish and benthic organisms in the wake of a pulse trawler operated under realistic field conditions and describe the role of stakeholder involvement in the planning of the research and the evaluation of the results.

MATERIALS AND METHODS

Field Experiments

General Set Up

Two field experiments were conducted on the 18th to the 19th of June 2019 and on the 15th of September 2020, hereafter referred to as Experiment 1 and Experiment 2. Each field experiment involved a commercial pulse trawler to create trawl tracks where organisms were exposed to the commercial pulse stimulus, and a commercial shrimp trawler to sample the pulse trawl track. Both pulse trawlers were double rigged with a trawl on either side of the vessel. Trawl tracks were created with 11m (Experiment 1) or 12m (Experiment 2) wide pulse trawls during experimental tows of 35 - 45 minutes. Within 15 - 30 minutes after pulse trawling, the shrimp trawler sampled the tow tracks for 10 min with a 9 m wide small-meshed shrimp beam trawl and at the same time took a control sample outside the pulse trawl track (**Figure 1**). Experimental conditions are presented in **Table 1**.

This design resulted in paired samples of treatments and controls for all tows. Experiment 1 consisted of two different pulse trawl treatments: pulse trawl tracks created by a complete pulse trawl (PULSE_CMPLT) and a pulse trawl with its netting and ground rope removed, resulting in only the seawing and pulse electrodes being towed over the seabed (PULSE_NO_NET). Experiment 1 was designed in cooperation with small-scale fishers and representatives of small-scale fisheries organizations (see below). Experiment 2 included only pulse treatment PULSE_CMPLT paired with its controls because in Experiment 1 no significant difference between the two pulse trawl riggings was found (**Supplementary Material SM1**). In total four tows were done in Experiment 1 with two tows per pulse trawl treatment. In Experiment 2 five tows were done, yielding five paired samples for PULSE_CMPLT and Control.

Trawl Specifications and Modifications

The trawl dimensions and specifications of the pulse and sampling trawls are presented in **Supplementary Material SM2**. To maximize the number of organisms that the sampling trawls could pick up from the seafloor, the conventional shrimp bobbin ground ropes of sampling trawls were replaced by heavy closed ground ropes consisting of rubber discs supplemented with 97 additional lead discs (0.9kg).

Pulse trawls had additional chains (10 m, Ø18 mm) attached to each end of the wings to create clearly visible slits on the seafloor that marked the boundaries of the pulse trawl tracks. The electrodes of the pulse trawl without ground rope and net were fixed in parallel position by one Dyneema® rope that connected

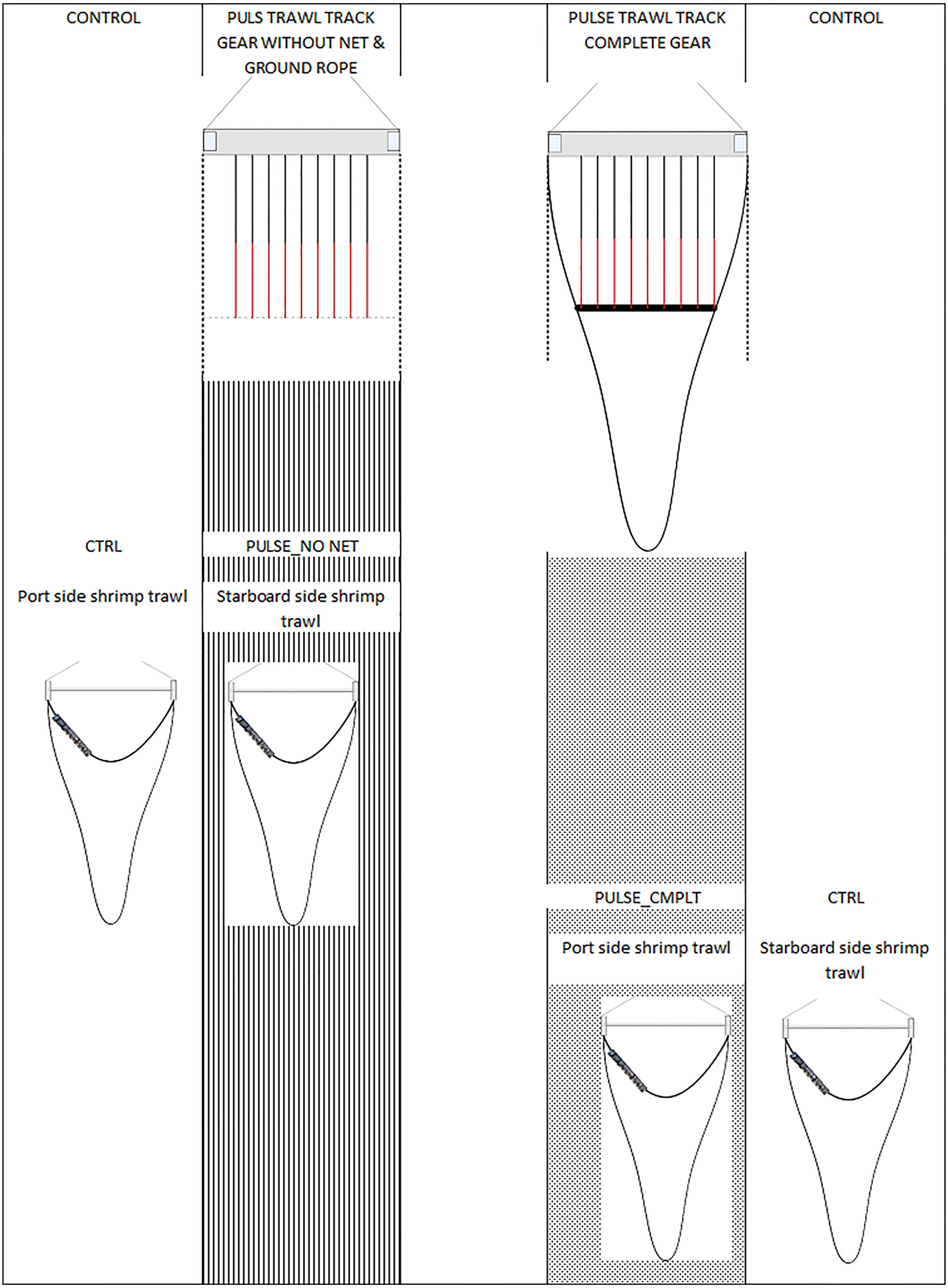

FIGURE 1 | Schematic presentation of the experimental design. Paired samples for PULS_NO NET and CTRL (Experiment 1 only) and for PULSE_CMPLT and CTRL (Experiment 1 and 2) were collected by deploying the shrimp trawls in and next to the respective pulse trawl tracks

TABLE 1 | Experimental conditions. Parameters were recorded per sampled tow. Presented are the minimum and maximum values recorded (range).

Parameter	Unit	Experiment 1	Experiment 2
Wave height[1]	m	–	0.3
Wind direction[1]		E-W-SW	S-N-NW
Wind speed[1]	Bft	0-2	2
Seafloor type[2]		Sandy/hard	Sandy/hard
Speed over water[3]	kts	4.7-5.0	–
Speed over seafloor[3]	kts	4.0 – 4.5	4.6
Sailing direction[3]	°	20 -200	16 - 200
Water depth[4]	m	21-23 [4]	22 – 25 [4]
Current direction[3]		NE	S - N
Current speed[3]	kts	0.8-2.2	0.1-1.1
Water temperature[5]	°C	11 – 13.2 [5]	–

[1]*Skipper's estimate.*
[2]*Skipper's knowledge & echo sounder equipment.*
[3]*Vessel's navigation equipment.*
[4]*Sea gauge pulse trawler.*
[5]*Sensor on pulse trawl.*

the aft ends of adjacent electrodes to prevent that electrodes could touch each other.

Deployment of Sampling Gear in Pulse Trawl Tracks

To deploy the sampling gear as precisely as possible in the trawl track, the shrimp trawler (with its trawls at the surface) followed the pulse trawler just outside its wake at a distance of approximately 120 m. A buoy on a 100 m rope, attached to the end of one of the booms of the pulse trawler, aided to maintain the shrimp trawler in proper position. Whilst navigating behind the pulse trawler, the shrimp trawler localized the pulse trawl on the seafloor and logged its track using a WASSP F3 multibeam sonar (WASSP Ltd, Auckland, New Zealand). When a clear trawl track had been observed, long enough for a 10 min sampling tow, the shrimp trawler returned to the starting position and deployed one of its trawls in a pulse trawl track and the other outside of the pulse trawl track (**Figure 1**). Towing time for sampling was limited to 10 minutes to minimize the impact of retention in the cod-ends on the sampled specimens. Towing speed over the seafloor of the sampling trawl ranged from 2.5 – 4.0 kts. All pulse trawl tracks and sampling tows were made against the tidal current to prevent benthic organisms to be washed out of the pulse trawl track by water currents. The pulse trawler refrained from discarding by-catches in the study area to prevent their inclusion in samples.

Underwater Video Recording

For each sampling tow, video recordings were made to be able to confirm the sampling from the pulse trawl tracks and to estimate the proportions of sampling inside the pulse trawl track. To record underwater videos the head rope of the sampling trawl was equipped with two forward looking cameras (GOPRO Hero 4) inside the right and left sides of the sampling trawl towed inside the pulse trawl track. Diving lights (Deep Blue 3500 lux) were installed next to each camera to increase visibility. To enable visual trawl path detection on the underwater video recordings a hard sandy sea bottom was chosen west of the Dutch coast (**Figure 2**). This sediment type is prevalent among the Dutch coast and provides reasonable visibility as the sand settles on the seabed after trawl passage.

Collection and Processing of Samples

The total catch weight of the sampling tows ranged between 4.6 and 21.5 kg. The samples collected in the port side and starboard side cod ends of the sampling trawls were discharged separately into 50L plastic baskets, each placed inside a plastic tub filled with surface seawater. Each tub was aerated to supply oxygen to the biota in the samples during their short storage prior to sample processing. Sub-samples of benthic organisms and fish were taken from these catches as follows. The content of each basket was homogenized by manual mixed before a sub-sample of approximately 2L was netted from the basket. To collect sub-samples from the entire water column, the net was dipped to the bottom of the basket and then filled up an upwards motion towards the surface. The sub-sample was placed in a 30L rectangular plastic tub filled with aerated seawater. Specimens of interest were manually picked from the tub and placed in water filled, aerated containers. If needed, a second or third sub-sample was taken from the basket holding the total catch to obtain at least 20 specimens per species. Sub-sampling of benthic organisms and fish was completed for both catches before we proceeded to assess the condition of the collected specimens. The order of sub-sampling and condition assessment for the port and starboard side catches was alternated between tows. To keep the time required to process all sub-samples within practical limits, sub-sampling was limited to six species in Experiment 1 and five species in Experiment 2 based on their abundance in the first samples (**Supplementary Material SM3**). The following species

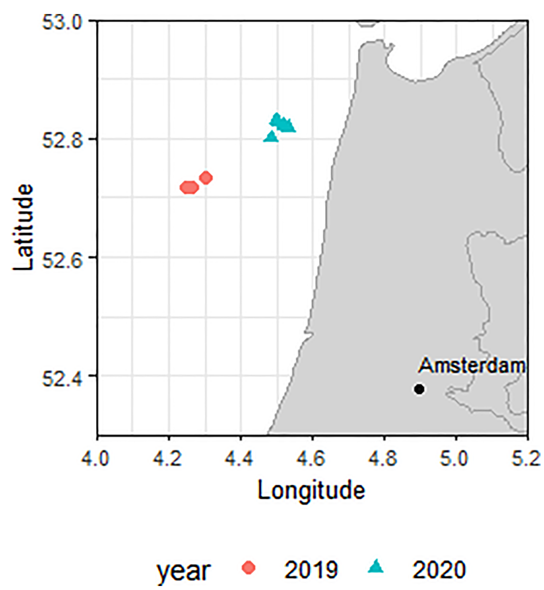

FIGURE 2 | Locations of the Experiment 1 (2019, red dots) and Experiment 2 (2020, blue triangles) tows.

were sampled: plaice (*Pleuronectus platessa*), dab (*Limanda limanda*), solenette (*Buglossidium luteum*, Exp. 1 only), flying crab (*Liocarcinus holsatus*), hermit crab (*Paguroidea* spp., Exp. 1 only), brittle star (*Ophiuroidea* spp.) and brown shrimp (*Crangon crangon*, Exp. 2 only).

Assessment of the Condition of Fish and Invertebrates

For all sub-sampled specimens (n = 20 per species) we established whether individuals were dead or alive. Specimens that displayed any kind of movement were considered to be alive. Specimens that displayed no movement or were crushed were considered to be dead. For 10 out of the 20 sub-sampled specimens per species treatment effects on condition were assessed in more detail by determining a range of damage scores (**Table 2**). Fish condition was assessed according to Van der Reijden et al. (2017), including damages to fins, skin and mucus layer and the presence of haemorrhages and summarized in a vitality class. Damage in invertebrates was assessed according to Bergman and Van Santbrink, (2000), including loss of limbs and crushing of carapax or disc. For brown shrimp we developed the 'jump reflex test' (**Table 2**). The abdominal muscle of brown shrimp is specialized in powerful contractions that enable the shrimp to jump backwards. This muscle has been shown to fatigue quickly (Hagerman & Szaniawska, 1986) making the 'jump reflex test' a suitable measure for condition and ability to display behaviour potentially essential for its survival.

Reconstruction of the Path of the Sampling Trawl

Observations by underwater videos of the shoes of the sampling trawling passing the slits drawn in the seafloor by the chains attached to each end of the pulse trawls and the electrodes of pulse trawl (PULSE_NO_NET only) allowed for the positioning of the sampling trawl relative to the pulse trawl track at multiple time points. The obtained set of positions were used to reconstruct the pathways of the sampling trawl for each haul and to estimate the area swept inside the pulse trawl track by the sampling trawl. **Figure 3** presents an example of a reconstructed trawl path of the sampling trawl relative to the pulse trawl tracks. A full set is presented in **Supplementary Material SM4**. The area sampled by the sampling trawl inside the pulse trawl track was expressed as percentage of the total area sampled for each tow **(Table 3)**.

Data Analysis

Differences in direct mortality between PULSE_NO_NET and PULSE_CMPLT were tested per species by Fisher's exact test using the raw counts of life and dead specimens in both treatments. As for none of the species tested a significant effect

TABLE 2 | Description of condition scoring.

Condition – All fish species	
Vitality class	**Description**
A	Fish lively, no visible signs of loss of scale or mucus layer.
B	Fish less lively, minor lesions and some scales missing, mucus layer affected up to 20% of skin surface area, some point haemorrhaging on the blind side.
C	Fish lethargic, intermediate lesions and some patches without scales, mucus layer affected up to 50% of skin surface area, 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% of the skin surface area, significant point haemorrhaging on the blind side.
Damage scores – All fish species	
Damage	Description (1 = present; 0 = absent)
Fins	Fins are damaged or split (including tail fin).
>50%	Damage to skin surface, scale or mucus layer at more than 50% of the dorsal body surface.
Head hemorrhages	Presence of a hemorrhage in the head of the fish
Hypodermic hemorrhages	Presence of a hypodermic hemorrhage
Intestines	Intestines are protruding or are visible through damaged body tissue of the fish.
Wound	Presence of a wound such that flesh is visible.
Damage scores – Invertebrates	
Damage	Description (1 = present; 0 = absent)
Limbs	Crabs & starfish: one or more limbs or arms (partly) lost.
Crushed	Carapace (crab, shrimp) or disc (starfish) damaged or crushed
Out of shell – undamaged	Hermit crabs: shell lost but animal undamaged
Out of shell - damaged	Hermit crabs: shell lost and animal damaged
Reflex – Brown shrimp	
Reflex	Description (1 = present; 0 = absent)
Jump	Shrimp placed in a tank jump backwards in response to a gentle touch of the head region with the observer's index finger

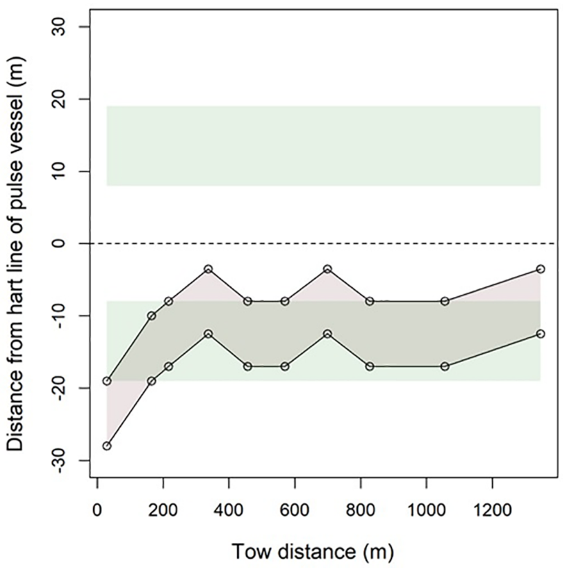

FIGURE 3 | Tracks of the starboard and port size pulse trawl (green) and reconstructed sampling track (grey) from the observed positions (o) of the shrimp trawl (o) of tow 1. The centerline of the pulse trawlers is positioned at 0 m on the y-axis.

was detected (SM 1), all observations for pulse trawl treatments PULSE_NO_NET and PULSE_CMPLT were merged into a single pulse trawl treatment (PULSE) for further analyses.

The direct mortality estimates may be affected by the proportion of the surface area sampled in the pulse trawl tracks (**Table 3**). The possible influence was tested using a binomial GLM model: $Y_i \sim \beta_1 + \beta_{2Xi} + \varepsilon$ where response variable $Y_i = n_i/N_i$, n_i is the number of dead animals and N_i is the total number of animals sampled in tow i, and the explanatory variable X_i being either the treatment (PULSE, Control: model m1) or the proportion of the trawl track of the pulse trawlers sampled (model m2) and ε is the bionomial error. In model 2, the proportion of the pulse trawl track sampled ranged between 0.43 and 0.94 in the treatment observations and were set at 0 for the control samples.

For direct mortality and individual reflex and damage scores 2x2 contingency tables were constructed per species for the raw counts of life and dead specimens (two levels) and treatment (Pulse vs Control) combination. For fish condition, expressed by vitality class A, B, C or D, 4x2 contingency tables were constructed per species for the counts per vitality class (four levels) and treatment (Pulse vs Control) combination. The contingency tables employed all observations of experiment 1 and 2. Fisher's Exact test was used to analyze the frequency distributions in these tables for significant treatment effects. Treatment effects were considered significant when p ≤0.05.

TABLE 3 | Estimates for the areas swept inside the pulse trawl track by the sampling trawl.

Experiment	Sampling tow	Area sampled inside pulse trawl track (% of total sampled area)
2019	1	80
	2	45
	3	49
	4	43
2020	5	89
	6	81
	7	61
	8	94

Swept areas are expressed as percentage of the total area swept by the sampling trawl during a sampling tow.

Interviews and Workshops

We held two workshops (2019 and 2020) and a series of interviews (2020) with small-scale fishers and representatives of small-scale fisheries organizations. We defined small-scale fishers for the purpose of this research as fishers engaged in gillnet fisheries, handling fisheries and shrimp fisheries. The objectives of the first workshop were to inform participants on the research objectives and to discuss experimental design options. Outcomes of this discussion were implemented in the design of Experiment 1. After reporting results of the Experiment 1 (Schram & Molenaar, 2019), we conducted ten interviews with fishers (8) and fisheries representatives (2). The interviews were performed in a semi-structured manner, using a predefined topic guide. Interviews were recorded with informed consent of the respondents and analyzed in a qualitative and quantitative manner using iterative coding in Atlas.ti 8.4.22.

The results of the interviews were validated in a second workshop in July 2020. Next to the validation of the results of the interviews, the workshop functioned as a way of informing small-scale fishers on results of Experiment 1, the design of Experiment 2 and providing space for additional input in the location and species to be examined in Experiment 2. The workshop was publicly announced and open for all Dutch small-scale fishers and representatives. Respondents of the interviews were personally invited to participate in the workshop. Seven fishers and representatives registered as participants. Three fishers/representatives actually joined the workshop. Reasons for the low number of participants could be a last minute emergency meeting of one of the fisheries organizations, or the good conditions for fishing that day.

RESULTS

Field Experiments

Direct Mortality Among Fish and Invertebrates

Overall, the large majority of sampled animals was alive upon sampling, resulting in survival (the reciprocal of mortality) ranging from 90-100% among treatments for the fish and the invertebrates. For all sampled species direct mortality did not differ between specimens collected inside the pulse trawl tracks (PULSE) and those collected in the control areas (Control) (Fisher's exact test p > 0.05, **Table 4**). These treatment effects could be tested for significance without taking the areas swept inside the pulse trawl tracks during the sampling tows into account (**Supplementary Material SM5**).

TABLE 4 | Acute mortality (% of total number of observations, N) of specimens sampled from the pulse trawl tracks (Pulse) and from the unfished control areas (Control).

Species	Pulse		Control		Fisher's Exact test
	%dead	N	%dead	N	p-value
Dab	5.9	170	10.1	179	0.17
Solenette	5.4	93	3.4	88	0.72
Plaice	0.0	115	0.8	127	1.00
Brittle stars	6.7	178	9.4	149	0.42
Hermit crabs	0.0	72	0.0	78	1.00
Flying crab	9.8	133	9.2	131	1.00
Brown shrimp	4.9	183	3.5	171	0.60

For none of the species a significant difference between Pulse and Control was detected (Fisher's exact test, p-value > 0.05).

Condition of Fish

For the three fish species sampled, most of the sampled fish were undamaged. The proportion of vitality class A ranged between 73% and 95% (**Table 5**). No difference in frequency distributions over the vitality classes A, B, C and D was detected between fish sampled from pulse trawl tracks (PULSE) or control areas (Control) (Fisher's Exact test p-values > 0.05, **Table 5**). Testing the separate damage types showed no significant difference between the fish sampled from the pulse trawl track or the unfished control area (Fisher's Exact test p-values > 0.05, **Table 6**).

Damages in Invertebrates

Damages observed in invertebrates are presented in **Table 7**. All hermit crabs we assessed were undamaged. Among flying crabs we observed missing limbs in 16-18% of the specimens where the majority of the brittle stars (58-63%) had lost at least part of one limb irrespective of the treatment. Differences in the occurrence of damages from either the pulse trawl track or the unfished control areas were not detected (Fisher's Exact test p-values > 0.05, **Table 7**).

Interviews and Workshops

In the first workshop, fishers expressed their concerns on pulse fisheries, which focused mainly on impacts on non-caught individuals, suspected use of higher than legally allowed voltages, (local) overfishing and the indirect impact of pulses on behaviour of round fish. Fishers experience a huge difference between fishing after a bottom trawl has passed, or fishing after a pulse trawl has passed. In the first case fishers have increased catches, while in the second they catch less or even nothing. Fishers suggested to do the experiments close to the 12-mile zone and include a PULSE_NO_NET treatment in the experiment to investigate mechanical versus electrical impacts. Fishers also suggested to use an extra heavy ground rope, to be able to catch everything that has been in contact with the pulse trawl. All these suggestions were included in the research design of the first experiment.

The interviews, which were performed after the results of the first experiment were published, showed mixed feelings among small-scale fishers with regard to pulse fisheries. They understand the urgency of innovation in the beam trawl sector, for which pulse could be a more efficient alternative. Some respondents therefore regard pulse fisheries as a good development, if it is not used to raise catches, but to decrease effort and expenses. The respondents state that by increasing catches, pulse fishers have flood the market, which led to decreased fish prices and has harmed the whole fisheries sector. Next to that, respondents argue that the introduction of pulse fisheries led to increased fishing pressure in certain areas and displacement of other types of fisheries. Within the small-scale fisheries sector, many fishers suspect that pulse fishers did not adhere to maximum peak voltage as established in the pulse exemptions. If pulse fishers would adhere to the regulations and would limit the amount of catches, respondents feel that pulse fisheries would not have had the impact on fish stocks and other fisheries as experienced today by small-scale fisheries. Besides the alleged misuse of pulse trawling, respondents also oppose to pulse trawling because of the exemption policy (only part of the fishers received an exemption), which lead to unfair competition among fishers.

When asked after the results of the first experiment, respondents declared that the results did not address their concerns. The experiment focused on benthic organisms, and although they understand the importance of benthic organisms for the North Sea ecosystem, they are more worried about the direct effects of pulse fishing on fish and shrimp. For shrimp, respondents worried that when they are pulsed, their reflexes make them jump, after which they can be hit by the ground rope and will end up dead on the seafloor instead of being caught or having escaped. Therefore, some fishers criticized the use of different gear combinations such as using the pulse trawl without using ground ropes, as this

TABLE 5 | Frequencies of vitality classes A-D (% of total number of observation, N) for plaice, dab and solenette sampled from pulse trawl tracks (Pulse) and unfished control areas (Control).

Species	Treatment	Total N	A (%)	B (%)	C (%)	D (%)	Fisher's Exact test p-value
Dab	Control	90	76.7	14.4	1.1	7.8	0.842
	Pulse	90	73.3	17.8	0.0	8.9	
Solenette	Control	40	95.0	2.5	0.0	2.5	0.177
	Pulse	40	80.0	12.5	0.0	7.5	
Plaice	Control	84	91.7	6.0	2.4	0.0	0.445
	Pulse	76	86.8	11.8	1.3	0.0	

For none of the species a significant difference between Pulse and Control was detected (Fisher's exact test, p-value > 0.05)

TABLE 6 | Presence of damages (response = 1, % of total number of observations, N) in dab, solenette and plaice sampled from pulse trawl tracks (Pulse) and unfished control areas (Control).

Species	Treatment	Total N	Fins split	> 50% scale loss	Head hemorrhages	Hypodermic hemorrhages	Intestines	Wounds
			(%)	(%)	(%)	(%)	(%)	(%)
Dab	Control	90	37	5	2	12	0	8
	Pulse	90	29	2	2	9	0	8
	p-value		0.91	0.94	0.69	0.83	1	1
Solenette	Control	40	0	0	0	0	0	0
	Pulse	40	0	5	0	5	0	0
	p-value		1	0.25	1	0.25	1	1
Plaice	Control	84	31	5	5	12	0	0
	Pulse	76	37	1	4	5	0	0
	p-value		0.27	0.96	0.74	0.96	1	1

Within species, no difference between Pulse and Control in the presence of damages was detected (Fisher's exact test, p-value > 0.05).

TABLE 7 | Presence of damages (response = 1, % of total number of observations, N) in brown shrimp, flying crab, hermit crab and brittle star sampled from pulse trawl tracks (Pulse) and unfished control areas (Control).

Species	Response	Pulse		Control		Fisher exact test
		Response=1 (%)	N	Response=1 (%)	N	p-value
Brittle stars	Missing limbs	63.3	98	58.2	91	0.55
	Crushed disk	0.0	98	0.0	91	1.00
Hermit crabs	Out of shell – undamaged	0.0	41	0.0	40	1.00
	Out of shell – damaged	0.0	41	0.0	40	1.00
Flying crab	Missing limbs	17.7	96	16.0	94	0.85
	Crushed carapace	4.8	96	3.2	94	0.72
Brown shrimp	Absence of jump reflex	53.6	110	55.0	111	0.89
	Crushed carapace	0.0	110	0.0	111	1.00

Within species, no difference between Pulse and Control in the presence of damages was detected (Fisher's exact test, p-value > 0.05).

does not represent real life pulse fishing practices. The fishers suggested to use "normal" gear and conduct the experiment within the 12-miles zone, for instance near Scheveningen or IJmuiden.

Except for the concerns which relate to the biological/ecological impact of pulse fisheries, the respondents were mostly concerned about the political developments in the fisheries sector. Small-scale fishers feel non-represented by the larger fisheries organizations and feel that their stakes are not represented in decision-making processes. They suspect that the North Sea fleet of bottom and pulse trawlers is regarded as a priority by the Dutch government, and that therefore the negative impact of pulse on other types of fisheries and marine nature is not studied extensively. Furthermore, some small-scale fishers feel that researchers are under pressure to deliver good results for the pulse gear. They stress that they trust the individual researchers, but not the politics behind the research.

In the second workshop we discussed the results of the interviews, to validate our findings. Fishers agreed with the abovementioned concerns raised by the respondents and with the suggestions for adapting the second experiment. Researchers discussed the suggestions together with the fishers, for instance with regard to the species which would be examined in the second experiment. Fishing within the 12-miles zone was suggested, to be able to look at mortality among shrimp and to study the area in which the small-scale fishers actually fish. As explained to the participants, conducting the experiment in the 12-miles zone would make the field work more challenging, as a special permit that allows the use of pulse trawlers of the large segment (11-12 m wide beams) has to be arranged and the water near the coast is much more murky, making it difficult to use cameras to ensure fishing in the wake of the pulse. However, the participants of the workshop emphasized that the closer to the coast the experiment would take place, the more relevant the results would be for small-scale fishers. Based on the results of the interviews and the discussion at the workshop, we decided that for the second experiment, the pulse trawler would have the same complete pulse gear on both sides and that a permit for conducting the experiment within the 12-miles zone would be requested.

DISCUSSION

This study was conducted because of concerns that pulse trawling causes direct mass mortality among benthic biota in its trawl track. These concerns are relevant in the assessment of impacts of pulse trawl fisheries and were not previously investigated *in situ*. To address the concerns properly, we engaged small-scale fishers in research design and studied their concerns through interviews and workshops.

We sampled three fish species and four invertebrate species from pulse trawl tracks on the seafloor shortly after pulse trawlers had passed as well as from unfished control areas. Sampled specimens were generally in good condition, especially the fish species, and direct mortality was low for all species. We found no evidence for higher direct mortality and poorer condition for any of the species sampled from the pulse trawl tracks compared to the unfished control areas. Although this study refutes the claim that pulse trawling causes a 'graveyard' by electrocution of marine life, we cannot rule out the possibility that intensive pulse trawling on a fishing ground could result in an aggregation of dead organisms on the sea floor, just like any other fishery that produces discards would do.

No difference in direct mortality among fish and invertebrates was detected for the complete pulse trawl and pulse trawl without net and ground rope. These treatments were designed to distinguish mechanical and electrical impacts of pulse trawling. It is reasonable to assume that in the case where a passing pulse trawl causes direct mortality, this effect would be larger for the complete pulse trawl because it combines mechanical and electrical impacts. However, direct mortality among biota collected from the pulse trawl track made by the complete pulse trawl was already low and did not differ between the trawled and the control area. Given the low direct mortality inflicted by pulse trawling a much larger number of sampling tows is required to test the effect between electrical impact and the mechanical impact from ground rope and net.

The direct mortality among the three fish species tested (plaice, dab and solenette) was low (between 0 to 10.1%) and did not differ significantly between the pulse trawl track and control treatments. Direct survival, the reciprocal of direct mortality, observed in the current study is comparable to the direct survival of plaice, sole, turbot, brill and thornback ray sampled from two hour tows by commercial pulse trawlers (Schram and Molenaar, 2018; Schram et al., *submitted*).

Exposure to electrical pulses may inflict internal injuries, such as spinal injuries and hemorrhages, which could result in a delayed mortality (De Haan et al., 2016; Soetaert et al., 2016a). Because the recorded injury rate in pulse trawl catches was low (<2.5%) in 14 dominant North Sea fish species sampled (Boute, 2022; Boute et al., 2022) it is highly unlikely that pulse-induced internal injuries will result in mass mortality. This conclusion also holds for the two species (cod, sandeel) for which higher injury rates were observed, because cod is only a small fraction of a beam trawl's catch (ICES, 2020), and because none of the sandeel exposed to a commercial pulse stimulus in a tank experiment developed internal injuries (Schram et al., 2022).

Delayed mortality may also occur due to the damage imposed by trawling and handling of the catch (Van der Reijden et al., 2017; Veldhuizen et al., 2018; Cook et al., 2019). A strong relationship was observed between fish condition directly after landing on deck and the long-term chances of survival of individual fish (Schram and Molenaar, 2018; Schram et al., *submitted*). In the current study we used the same method as in Schram and Molenaar (2018) to determine the condition of individual fish and found that the large majority of fish were in excellent condition (vitality class A) and did not show any sign of damage. This is in stark contrast to the condition recorded in commercial catch of pulse trawlers. Jointly taken, we consider it unlikely that fish exposed to pulse trawls shown high delayed mortality. Dedicated survival studies in which sampled fish are kept in captivity to monitor their long-term survival are needed to corroborate this.

For dab we observed 'wounds' in all treatments with an incidence of 7% in the sampled fish. Without exception these wounds were skin ulcerations which are prevalent in wild common dab (Vercauteren et al., 2018) which we consider to be unrelated to the current experimental treatments.

Similar to our observations on fish, direct mortality among the tested invertebrate species was low and ranged from 0% to 10% across treatments. Our observations correspond with the findings of Bergman et al. (1992) who studied direct mortality among benthic invertebrates escaping through 90 mm meshes of tickler chain beam trawls. Bergman et al. (1992) collected specimens in narrow meshed cover nets and found direct survival of brittle star and swimming crabs to be nearly 100%. In our study, direct mortality did not differ between the pulse trawl track and control treatments. To what extent this low direct mortality is indicative for the long-term survival is unknown because unlike the fish in this study, we have no information on the long-term survival in relation to the condition of individual invertebrates. Dedicated survival studies similar to those described for fish are required to establish long-term survival.

Condition of flying crabs and brittle stars was assessed by checking individuals for crushed carapaces (crabs) or discs (brittle stars) and for (partly) missing limbs. None of the assessed brittle stars and only a few flying crabs were found to be crushed, which indicates that the mechanical impacts of the passing pulse trawl and capture by the sampling trawl are probably limited. Missing limbs were observed across treatments in both invertebrate species but no difference between the pulse trawl track and control treatments were detected. Since we did not determine whether the loss of a limb was recent, we cannot attribute loss of limbs to impacts of the pulse or sampling trawl nor exclude such impacts. With an incidence of 65% to 90% across treatments the majority of the brittle stars showed some degree of damage. This may be a reflection of the sensitivity of this invertebrate to the mechanical impacts of a trawl. Although long-term effects of loss of limbs is unknown, it is clear that the impact of a pulse trawl does not cause additional mortality due to loss of limbs compared to other trawls with comparable mechanical impact.

The abdominal muscle in brown shrimp is specialized in powerful contractions enabling shrimp to jump backwards and has been shown to fatigue quickly (Hagerman & Szaniawska, 1986). Our observation that irrespective of the treatment, the jump reflex was absent in almost half of the tested brown shrimp, may indicate fatigue of the abdominal muscle and thus a compromised escape mechanism in these specimens. This is an important result, as it directly addresses one of the concerns raised by small-scale fishers, who are afraid that the combination of the pulse trawl and a ground rope would harm shrimp instead of catching shrimp. However, absence of the jump-reflex cannot be attributed to exposure to electrical stimulation because no treatment effect was detected; it occurred in equally high numbers among shrimp sampled from the pulse trawl track as the unfished control areas. It seems therefore more likely that it is an effect of exhaustion due to the catch process by the sampling trawl.

Condition of hermit crabs was assessed by checking individuals for non-specified, visually detectable damage while being in or out of its shell. All assessed hermits crabs were found to be undamaged. This either suggests that hermit crabs are very resilient to the impacts inflicted by the passing pulse trawl and catching by the sampling trawl, or that our condition assessment criteria lack sensitivity to detect impacts by the pulse and sampling trawl.

Critical to the credibility of this study is the assurance that specimens were actually sampled from the pulse trawl tracks. Our underwater video observations revealed that during sampling tows the sampling trawl moved in and out of the pulse trawl track, confirming that part of the specimens were indeed sampled inside the pulse trawl tracks. Based on the analyses of the underwater video observations the area sampled inside the pulse trawl tracks was estimated to range from 43% to 94% of the total swept area among the nine sampling tows. Our binomial GLM modelling approach revealed that direct mortality estimates were not affected by the proportion of the pulse trawl track sampled. Treatment effects could consequently be tested for significance without taking into account that the area swept inside the pulse trawl track. The catches of marketable sole (>24 cm) of the pulse trawlers whilst making the pulse trawl tracks as recorded by the skippers were within the range of catch rates of other pulse trawlers fishing in the same area and the same week (**Supplementary Material, SM6**). This corroborates that the pulse stimulus was switched on during the experimental tows. It is well known that by switching off the pulse stimulus, the catch rate of sole drops by about 80% (Rijnsdorp et al., 2021).

The sampling trawl in this experiment was equipped with a modified ground rope to collect as much specimens from the seafloor as possible. It should be noted however that we probably sampled exclusively from the seafloor as is reflected by the species we sampled. Any biota residing in the seafloor did not appear in our samples and we therefore have no data on the effect of a pulse trawl on the infauna. The absence of infauna in our samples shows that pulse field exposure does not stimulate infauna to immediately emerge to the surface of the sediment.

The results of the field work in 2019 were shared with fishers through a report and article in the Dutch newspaper for the fisheries sector. After publication of the results, we saw a shift in the topics raised by small-scale fishers in the interviews and the second workshop. Instead of focusing on the scientific uncertainty surrounding the pulse trawl, fishers focused on management and political issues, such as the role of the Dutch government in stimulating pulse fisheries and alleged misuse of pulse techniques by Dutch fishers. The shift from knowledge related towards management and political concerns could be explained in several ways. First, the results of the first experiment showed no direct mortality of benthic organisms after a pulse trawler has passed. These first results, which were known to most fishers who participated in the interviews and second workshop, could already have influenced their perceptions of pulse fisheries. Second, the worries concerning direct mortality were mostly raised by English and French fishers, and might not have been the biggest concern of Dutch small-scale fishers from the start. However, in our research we put the focus on this topic, which might explain the interest of small-scale fishers in the direct mortality in the wake of the pulse during the first workshop. To understand the direct impact of the results of this study on perceptions of this particular topic, English and French fishers should be included in the study. Third, the engagement of fishers in research design and the interest in the concerns of fishers in general, for which there was space in the interviews and workshops, might have led to increased trust between fishers and researchers. By engaging stakeholders in research, trust in science and scientific advice can increase (Röckmann et al., 2015). Fishers value face-to-face contact (Gray et al., 2005) and trust between fishers and researchers is built through long-term relationships, regardless of the specific research topic (Ebel et al., 2018). Furthermore, collaborative learning processes and including lay expertise can advance the scientific understanding of the problem at hand (Röckmann et al., 2015). The shift from discussions on the credibility of the knowledge produced in pulse research towards more management related discussions might therefore be an indication that through engagement of fishers the credibility of the current study has increased. Coming back to the third explanation, the change in perceptions witnessed in this study might be less related to the absence of increased direct mortality of fish and benthic organisms in the wake of the pulse than to the participative approach taken by the researchers. As research in the environmental domain and especially in nature resource management fields such as fisheries often aim to address concerns raised by one or more stakeholder groups, we would advise to include these stakeholders in an earliest stage as possible in delineating the research question and developing the research design. Moreover, we recommend to keep them engaged throughout the research process, to enable research to be both relevant and credible to the people it matters to. Next to the interviews and workshops, stakeholder engagement in this study also included indispensable contributions of the three commercial fishing vessels to successfully conducting the field experiments. These demanded skill, dedication and commitment of skippers and crews. Especially positioning and keeping the sampling trawl inside the pulse trawl track was a major challenge for the skipper, to which he was committed to accomplish or he felt his reputation as a skipper would be tarnished. Clearly the high level of commitment of these stakeholders was indispensable to the success of the field experiments.

In conclusion, our study refutes the claim that pulse trawling would result in mass mortality among fish and invertebrate species. For all species tested, our field experiment did not find any support for direct mortality from the exposure to a pulse stimulus, consistent with the results of laboratory exposure experiments (review in ICES, 2020). Additionally, our study showed the importance of stakeholder engagement in problem-framing and research design, especially in the case of applied and politically sensitive research domains. By engaging stakeholders the credibility of our research improved, and we were able to identify other and underlying preoccupations regarding our research topic.

DATA AVAILABILITY STATEMENT

The data underlying this article will be shared on reasonable request to the corresponding author.

ETHICS STATEMENT

Ethical review and approval was not required for the animal study because although the study involves the sampling and handling of vertebrates, the study is not considered an animal experiment under the Dutch animal experimentation act.

AUTHOR CONTRIBUTIONS

Conceptualization: ES, PM, and SK; design and methodology: ES, PM, and SK; performing field experiments: ES and PM; Interviews and workshops: SK and PM. Collection of data: ES and PM; data analysis: ES and AR; writing original draft: ES, PM, SK, and AR; Writing – review and editing: ES, PB, SK, and AR. All authors contributed to the article and approved the submitted version.

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SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fmars.2022.907192/full#supplementary-material

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Conflict of Interest: The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.