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Morphometric characteristics of Antarctic krill (*Euphausia superba*) and finfish bycatch in the krill fishery in the waters of South Orkney Islands during the 2022/23 fishing season

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Determination of bar spacing of bycatch reduction devices (BRDs) should consider species composition and morphometric characteristics (particularly width) of target species krill and bycatch. This study conducted a scientific investigation of the finfish bycatch in the Antarctic krill (*Euphausia superba*) trawl fishery by the fishing vessel SHEN LAN in the waters surrounding the South Orkney Islands from December 24, 2022, to February 20, 2023. The results show that scientific observers sampled 676 individuals of finfish bycatch. Of these, 665 were identified to species (17 species from 8 families), while the remaining 11 specimen were juveniles of the *Nototheniidae* family that could not be identified to the species level. IRI (index of relative importance) calculations showed three dominant (IRI value greater than 1,000) finfish bycatch species (*Champsocephalus gunnari*, *Pseudochaenichthys georgianus*, and *C. aceratus* from the *Channichthyidae* family) and four important (IRI value between 1,000 and 100) finfish bycatch species (*Electrona carlsbergi* and *Gymnoscopelus nicholsi* from the *Myctophidae family*, *Gobionotothen gibberifrons* from the *Nototheniidae* family, and *Notolepis coatsi* from the *Paralepididae* family). Our study provides morphometric data (particularly body width) that is crucial to model the potential for bycatch reduction by use of bycatch reduction devices (BRDs) and to determine the appropriate candidate bar spacings for BRD sea trials. Predictions suggest that a 10 mm (the maximum body width of krill) bar spacing releases a significant amount of dominant and important bycatch species (93.94% of *C. gunnari*, 53.99% of *P. georgianus*, 76.25% of *C. aceratus*, and 100% of *G. gibberifrons*). Reduced fishing pressure would reduce the risks to dominant and important bycatch species to make the krill fishery sustainable. We recommend that future BRD sea trials should initially test a 10 mm bar spacing. If marked loss of krill is observed, wider spacings (e.g. 15 mm) must be tested.

KEYWORDS
Southern Ocean, trawling, icefish, lanternfish, bycatch exclusion device

1 Introduction

Antarctic krill (*Euphausia superba*, hereafter "krill") is abundant and widely distributed in the Southern Ocean (Atkinson et al., 2008). It also has the largest catchable biomass in the world. As a source of protein for human and animal consumption, commercial fishing for krill is expected to increase in the future with new and efficient fishing technologies (Gigliotti et al., 2008; Nicol et al., 2012). The annual krill catch has increased from around 100,000 tons at the beginning of the 21st century to 400,000 tons in recent years (CCAMLR, 2022a). The total allowable catch for the southwest Atlantic is currently about 5.61 million tons annually, according to CCAMLR.

Krill swarms are typically found at depths of 0-200 m. The midwater trawls are the most effective fishing gear for krill (Everson et al., 1992; Nicol and Endo, 1999; Siegel and Watkins, 2016). Commercial krill trawls typically use double netting because of the small size (<60 mm length) of the krill. Small-mesh liners are fitted in a trawl body and codend to reduce krill catch loss through meshes (Everson et al., 1992; Wang et al., 2021; CCAMLR, 2023a). This design makes it challenging for non-target organisms to escape once they enter the trawl. Therefore, the Commission for the Conservation of Antarctic Marine Living Resources (CCAMLR) mandated that all krill trawls must have an "exclusion device" to prevent the accidental catch of whales, seals, and other large marine organisms (CCAMLR 2023b).

An "exclusion device" usually involves one of two main types of separator netting panels. The first type covers the mouth of the trawl to prevent large marine organisms from entering the trawl. The other type is a slanting net panel placed in the forward part of the belly that guides large marine organisms towards a release hole in the top or side panels. The mesh size of the separator netting is usually 200-300 mm, which balances the towing resistance and the performance to prevent large marine organisms from entering the trawl (CCAMLR 2023c). However, smaller organisms, such as finfish can pass through the separator netting and enter the codend. Large quantities of finfish bycatch may obstruct the transportation pipeline and cause stoppage during the fishing process. Additionally, it is challenging to separate finfish bycatch from the krill in both the capture and onboard processing phases.

We have developed an anti-blocking exclusion device to reduce finfish bycatch in krill trawls (Figure 1). This device is placed in the extension section of the trawl and permits the entry of krill into the codend through the bar spacings. In contrast, larger-sized bycatch cannot pass through bar spacing and will escape by activating a pressure spring to open a releasing vent. Determination of bar spacing should consider morphometric characteristics (particularly width) of target species krill and bycatch, particularly the vulnerable species (Hornborg et al., 2013; Gamaza et al., 2015; Tokac et al., 2016; De Juan et al., 2020).

Therefore, we collected finfish bycatch in krill trawls by a commercial F/V SHEN LAN in the waters of the South Orkney Islands during the 2022/23 fishing season. We analyzed the morphometric characteristics of the bycatch species to determine the appropriate bar spacing of rigid bycatch exclusion devices. The implementation of such devices is crucial for reducing the fishing impact on vulnerable finfish species and thereby ensuring a responsible krill fishery.

2 Materials and methods

2.1 Date and position of the bycatch sampling

Scientific observers collected finfish bycatch specimens from the conveyor belt outlet in the processing room onboard F/V SHEN LAN in the waters of South Orkney Islands. The vessel used conventional and continuous fishing methods, with a 400 mm mesh-sized netting panel covering the trawl mouth opening to prevent the accidental catch of large marine organisms. The entire trawl aft of the marine mammal exclusion device (Figure 2) were equipped with small-mesh (16 mm) liners.

Continuous fishing operations were carried out in 404 hauls between December 22, 2022, and January 15, 2023. Hauls are defined as the catch taken during a 2-hour period (i.e., 00.00-

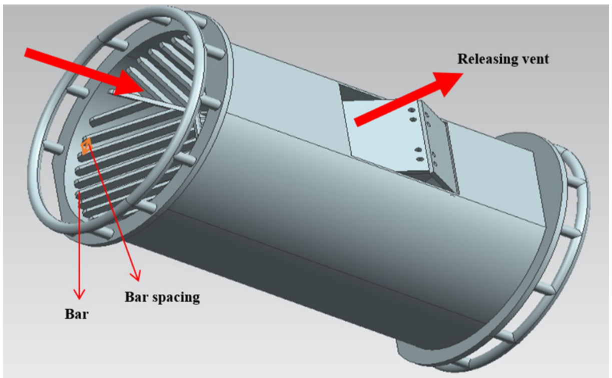

FIGURE 1
Schematic diagram for the principle of Anti-blocking bycatch exclusion device.

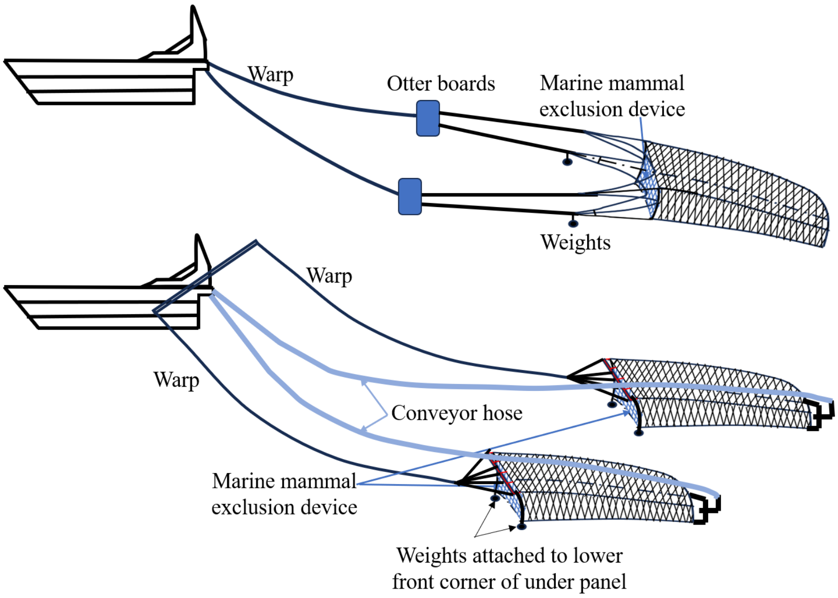

FIGURE 2
Schematic diagram of conventional (upper) and continuous krill trawling (lower).

02.00 hours, 02.00-04.00 hours, etc.), except for the first haul and last haul based on the procedure of CCAMLR (CCAMLR, 2019). The daily krill catch was estimated using a flow scale and allocated to each haul based on its holding tank volume. Conventional trawling operations were carried out in 249 hauls from January 20, 2023, to February 25, 2023. Finfish bycatch specimens were collected from 56 hauls; 15 hauls of continuous fishing and 41 hauls of conventional trawling. Sampling positions (Figure 3) were plotted using the package "ggOceanMaps" (Vihtakari, 2024) in R version 4.1.0 (R Core Team, 2024). Detailed information on each haul is provided in Appendix 1.

2.2 Measurement of krill and finfish bycatch

The identification of species followed the manual "By-catch identification and educational material for use by observers on

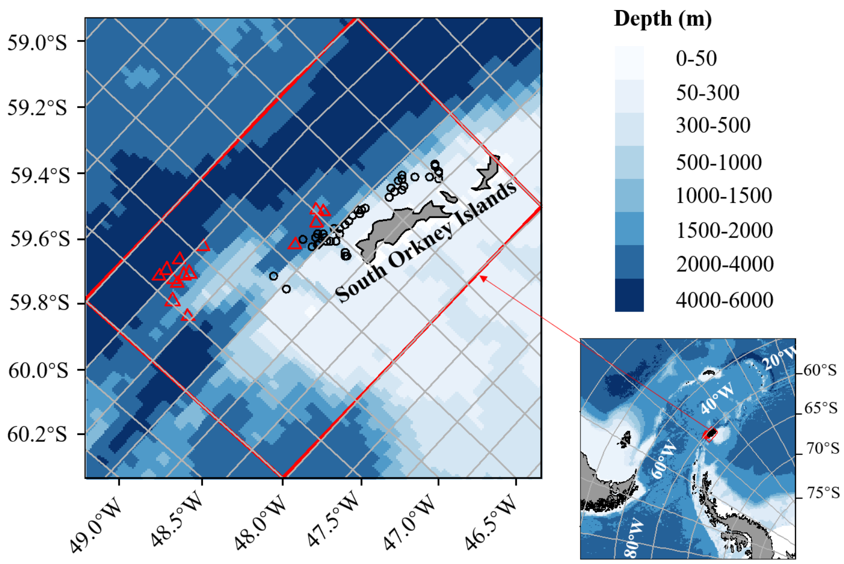

FIGURE 3
Sampling positions for continuous fishing (red triangles) and conventional trawling (black dots) carried out by F/V SHEN LAN in the waters of the South Orkney Islands. The position on the map is the median of the starting and ending longitudes and latitudes of each haul.

vessels" (https://www.ccamlr.org/en/science/information-technical-coordinators-and-scientific-observers) and other related observer training materials. Fishing vulnerability is the intrinsic extinction vulnerability of marine fishes to fishing that is calculated based on life history and ecological characteristics (e.g., maximum length, age at first maturity, longevity, fecundity, etc.) available through FishBase (Froese and Pauly, 2024. www.fishbase.org) by retrieval using scientific names. Two scientific observers onboard F/V SHEN LAN measured morphometric characteristics-body length, height, width, and weight -of fresh krill and finfish bycatch specimens. Krill body lengths were measured from the front of the eye to the tip of the telson based on CCAMLR standard protocols (CCAMLR, 2022b). Finfish bycatch fork lengths were measured from the snout tip to the base of the caudal fin's median rays (Mazhirina, 1990). Body widths and heights correspond to the maximum sections (Herrmann et al., 2009; Tokac et al., 2016) by moving and adjusting the vernier caliper while barely touching the body. Body lengths less than 150 mm, widths, and heights were measured using a digital vernier caliper with a range of 0-150 mm and a resolution of 0.01 mm (Ningbo Deli Tools Co., ltd). Body lengths ranging from 150 mm to 350 mm were measured using a grid ruler with a range of 0-350 mm and a resolution of 1 mm. Body lengths greater than 350 mm were measured using a tape with a range of 0-100 cm and a resolution of 1 mm. Body weights of less than 1,000 g were measured using a traditional balancing hanging scale (scale 1 with a range of 0-10 g and a resolution of 0.1 g; scale 2 with a range of 0-1,000 g and a resolution of 5 g). Body weights over 1,000 g were measured using a Marel marine scale with a range of 0-30 kg and a resolution of 10 g.

2.3 Data analysis

2.3.1 Index of relative importance of bycatch

The IRI (index of relative importance) was calculated to determine the importance of each bycatch species using the following Equation (1):

$$IRI = (N + W) \times F \quad (1)$$

where N is the numerical percentage, W is the weight percentage, and F is the frequency of occurrence percentage (Hart et al., 2002). Dominant bycatch species have an *IRI* value greater than 1,000, important bycatch species have an *IRI* value between 1,000 and 100, common bycatch species have an *IRI* value between 100 and 10, and rare bycatch species have an *IRI* value less than 10 (Chen et al., 2022; Luo et al., 2023).

2.3.2 Statistical analysis and the relationship between morphometric characteristics

Morphometric characteristics of krill were analyzed along with dominant and important finfish bycatch. These analyses were conducted using Microsoft Office Excel (2016) software, which provided minimum, maximum, mean value, and standard deviation statistics. The length distributions and the relationships of body height and width at length were plotted using the "GGally" package (Schloerke et al., 2021) in R version 4.1.0 (R Core Team, 2024).

2.3.3 Release ratio of the bycatch species for different bar spacing of size-selective grids

The release ratio is the bycatch species body width ratio wider than the bar spacings. We modelled the release ratio for different bar spacings solely based on individual fish width measurements of dominant and important bycatch species by using the following Equations (2) and (3):

$$R_{nis} = \frac{N_{is}}{N_s} \times 100\,\% \quad (2)$$

$$R_{wis} = \frac{W_{is}}{W_s} \times 100\,\% \quad (3)$$

where R_{nis} is the release ratio in terms of number for bycatch species s and bar spacing i; N_{is} is the number of bycatch species s and bar spacing i; N_s is the total number of bycatch species s; R_{wis} is the release ratio in terms of weight for bycatch species s and bar spacing i; W_{is} is the weight of bycatch species s and bar spacing i; W_s is the total weight of bycatch species s.

3 Results

3.1 Species composition and index of relative importance of finfish bycatch

The observers recorded 676 specimens of finfish bycatch in the waters around South Orkney Islands during the study period. Of these, 665 individuals were identified as belonging to 17 species from 8 families, while 11 juveniles of the *Nototheniidae* family could not be classified to a lower taxonomic level. There were six species of the *Channichthyidae* family, four or five species of the *Nototheniidae* family, two species of the *Myctophidae* family, and only one species each of *Paralepididae*, *Artedidraconidae*, *Macrouridae*, *Gempylidae*, and *Centrolophidae* families. The IRI calculations showed three dominant finfish bycatch species (*Champsocephalus gunnari*, *Pseudochaenichthys georgianus*, *Chaenocephalus aceratus*) and four important bycatch species (*Electrona carlsberg*, *Gymnoscopelus nicholsi*, *Gobionotothen gibberifrons*, *Notolepis coatsi*) (Table 1; Figure 4).

3.2 Dominant and important bycatch species caught in conventional and continuous trawling

According to the index of relative importance analysis, dominant and important species of finfish bycatch differed between conventional trawling and continuous fishing (Table 2). Fishing depth of conventional trawling operations ranged from the surface to nearly 300 meters in shallow areas. Dominant bycatch were three species (*C. gunnari*, *P. georgianus*, and *C. aceratus*) of *the*

TABLE 1 Species composition, fishing vulnerability, and index of relative importance of finfish bycatch in the krill trawl fishery in the waters of South Orkney Islands from December 24, 2022, to February 20, 2023.

Serial number	Family name	CCAMLR Codes	Species Name	Common Name	Fishing Vulnerability[1]	Occurrences of observed (Hauls)	Catch in number	Weight[2] (g)	IRI[3]
1	*Channichthyidae*	ANI	*Champsocephalus gunnari*	Mackerel icefish	Moderate (35/100)	24	99	42,666.7	**1,828.6**
2		JIC	*Neopagetopsis ionah*	Crocodile icefishes	Moderate (42/100)	3	11	1,612.0	14.4
3		KIF	*Chionodraco rastrospinosus*	Ocellated icefish	Moderate to high (51/100)	3	3	764.0	5.1
4		SGI	*Pseudochaenichthys georgianus*	South Georgia icefish	Moderate to high (47/100)	28	180	45,396.8	**2,822.1**
5		SSI	*Chaenocephalus aceratus*	Blackfin icefish	Moderate to high (54/100)	17	80	33,106.2	**1,019.3**
6		TIC	*Chionodraco hamatus*		High (61/100)	1	3	101.0	0.9
7	*Myctophidae*	ELC	*Electrona carlsbergi*	Carlsberg's lanternfish	Low (24/100)	15	80	433.0	324.6
8		GYN	*Gymnoscopelus nicholsi*	Nichol's lanternfish	Low (10/100)	8	69	1,971.2	164.3
9	*Nototheniidae*	NOC	*Notothenia coriiceps*	Black rockcod	High (60/100)	2	2	2,040.0	5.8
10		NOG	*Gobionotothen gibberifrons*	Humped rockcod	Moderate (42/100)	12	43	20,441.0	424.0
11		GTO	*Pagothenia borchgrevinki*	Bald rockcod	Moderate to high (52/100)	1	1	30.0	0.3
12		NOR	*Notothenia rossii*	Marbled rockcod	High (63/100)	1	1	514	0.87
13		NOX	*Nototheniidae*	Antarctic Rockcods	Not applicable[4]	6	11	33.8	17.67
14	*Paralepididae*	NTO	*Notolepis coatsi*	Antarctic jonasfish	Moderate (36/100)	27	89	2,683.1	719.73
15	*Artedidraconidae*	PLF	*Artedidraconidae*	Barbeled plunder fishes nei	Not applicable[4]	1	1	0.18	0.26
16	*Macrouridae*	RTX	*Macrouridae*	Grenadiers, rattails nei	Not applicable[4]	1	1	2.8	0.27
17	*Gempylidae*	PDG	*Paradiplospinus gracilis*	Splendor escolor	Moderate (41/100)	1	1	37	0.31
18	Centrolophidae	ICA	*Icichthys australis*	Southern driftfish	Moderate to high (52/100)	1	1	430	0.77

[1]Fishing vulnerability of bycatch species was acquired from FishBase, which is based on Cheung et al. (2005) models.
[2]Weight, Total weight of bycatch species in all observed hauls.
[3]IRI, Index of Relative Importance. The bold values indicate dominant bycatch species.
[4]Not applicable, Fish could not be classified to a lower taxonomic level.

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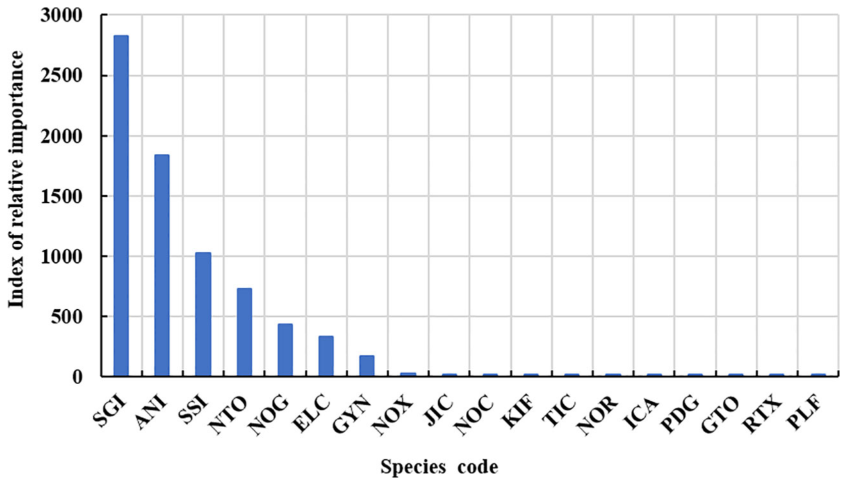

FIGURE 4
Index of relative importance for each finfish bycatch species caught in the krill trawl fishery by F/V SHEN LAN in the waters of South Orkney Islands from December 24, 2022, to February 20, 2023.

Channichthyidae family. These species were mainly caught in hauls at fishing depths deeper than 50 meters. Important bycatch species, *G. gibberifrons* was caught primarily in the hauls taken at fishing depths deeper than 120 meters, *G. nicholsi* was caught in the hauls taken at fishing depths shallower than 120 meters, while *N. coatsi* was caught in the hauls taken at all fishing depths. In comparison, continuous trawling operations ranged from the surface to nearly 120 meters due to the depth limit set by the conveyor hose. Dominant and important bycatch species caught in continuous fishing were mostly mesopelagic *E. carlsbergi*, *N. coatsi*, and *P. georgianus* (Figure 5).

3.3 Morphometric characteristics of krill and dominant and important bycatch

Krill had a unimodal size distribution. Body lengths ranged from 30.64 mm to 59.19 mm, with a mean value of 48.31 mm (± 5.64 mm, Standard deviation). Body heights ranged from 3.53 mm to 12.10 mm, with a mean body height of 6.72 mm (± 1.44 mm). Body widths ranged from 2.81 mm to 9.92 mm, with a mean body width of 5.39 mm (± 0.36 mm). Contrary, dominant finfish bycatch species (*C. gunnari*, *P. georgianus*, and *C. aceratus*) had wide and multimodal length distributions, from the smallest fish (in their first year) to largest, reaching approximately 50 cm in body length. For *C. gunnari*, body lengths ranged from 29.4 mm to 452.0 mm, heights ranged from 4.7 mm to 78.6 mm, and widths ranged from 3.1 mm to 60.0 mm. For *P. georgianus*, body lengths ranged from 25.2 mm to 471.0 mm, heights ranged from 4.3 mm to 107.0 mm, and widths ranged from 3.3 mm to 76.8 mm. For *C. aceratus*, body length ranged from 21.0 mm to 495.0 mm, heights ranged from 2.6 mm to 82.9 mm, and widths ranged from 1.7 mm to 69.3 mm. Of the important bycatch species, *E. carlsbergi*, *G. nicholsi* and *G. gibberifrons* had unimodal length distributions with body lengths of 74.3 mm (± 9.8 mm), 138.5 mm (± 12.4 mm) and 321.9 mm (± 20.6 mm), respectively, while *N. coatsi* had a bimodal length

TABLE 2 Dominant and important bycatch species caught in conventional and continuous fishing by F/V SHEN LAN in the waters of South Orkney Islands from December 24, 2022, to February 20, 2023.

Species Name	Conventional trawling				Continuous fishing			
	Occurrence (Hauls)	Catch in number	Weight[1] (g)	IRI[2]	Occurrence (Hauls)	Weight[1] (g)	Catch in number	IRI[2]
C. gunnari	22	99	42,666.7	**2,463.1**	–	–	–	–
P. georgianus	24	174	45,106.8	**3,556.5**	3	290	6	**566.7**
C. aceratus	16	80	33,106.2	**1,411.8**	–	–	–	–
E. carlsbergi	6	7	35.3	18.4	9	397.7	73	**3,880.4**
G. nicholsi	5	66	1,939.0	**157.7**	3	32.2	3	56.1
G. gibberifrons	11	43	2,0441.0	**569.1**	–	–	–	–
N. coatsi	11	65	2,135.1	**345.8**	12	548	24	**4,283.7**

[1]Weight, Total weight of bycatch species in all observed hauls.
[2]IRI, Index of Relative Importance. The bold values indicate dominant bycatch species.

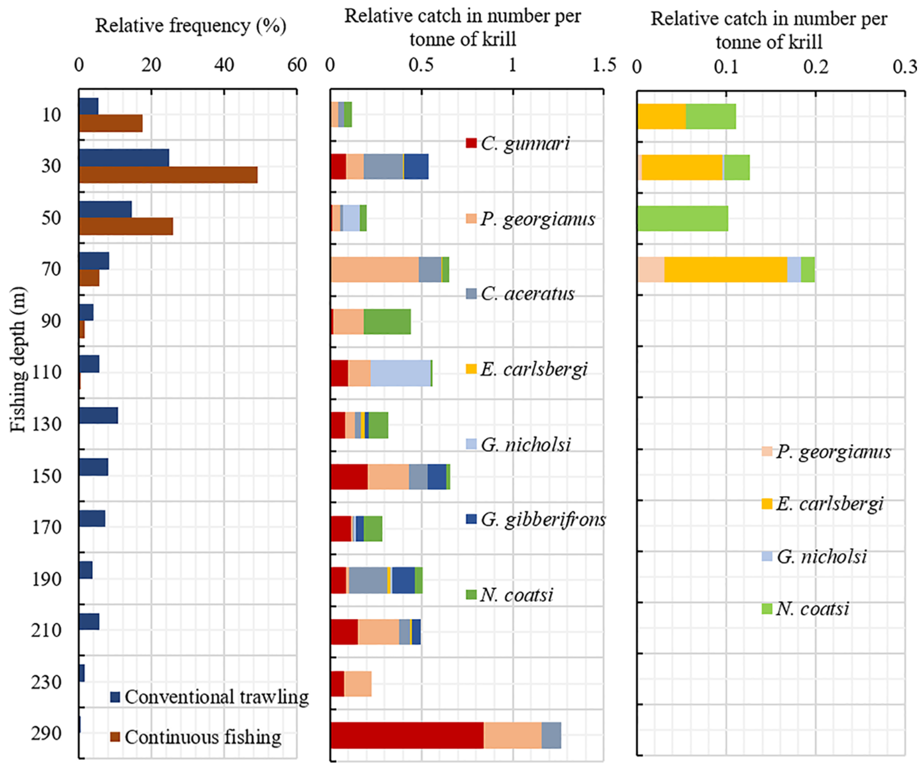

FIGURE 5
Left: Relative distribution of fishing depth for hauls taken by conventional trawling and continuous fishing. Relative catch in number per ton of krill of dominant and important finfish bycatch species caught in conventional (Middle) and continuous trawling (Right) at different fishing depths in waters of South Orkney Islands from December 24, 2022, to February 20, 2023.

TABLE 3 Body lengths, heights, and widths of dominant and important bycatch species caught in the krill trawls taken by F/V SHEN LAN in the waters of the South Orkney Islands from December 24, 2022, to February 20, 2023.

Species code (Species name)	Measure types	Number measured	Minimum value	Maximum value	Mean value	Standard deviation
KRI (*E. superba*)	Length (mm)	193	30.64	59.19	48.31	5.64
	Height (mm)		3.53	12.10	6.72	1.44
	Width (mm)		2.81	9.92	5.39	0.97
ANI (*C. gunnari*)	Length (mm)	99	29.4	452.0	310.3	142.5
	Height (mm)		4.7	78.6	44.9	23.8
	Width (mm)		3.1	60.0	37.1	18.6
SGI (*P. georgianus*)	Length (mm)	146	25.2	471.0	181.2	162.8
	Height (mm)		4.3	107.0	33.0	32.5
	Width (mm)		3.3	76.8	26.3	25.2
SSI (*C. aceratus*)	Length (mm)	80	21.0	495.0	307.2	160.9
	Height (mm)		2.6	82.9	48.1	26.4
	Width (mm)		1.7	69.3	36.3	19.8
ELC (*E. carlsbergi*)	Length (mm)	78	49.8	96.5	74.3	9.8
	Height (mm)		10.7	21.6	17.2	2.2

(Continued)

TABLE 3 Continued

Species code (Species name)	Measure types	Number measured	Minimum value	Maximum value	Mean value	Standard deviation
	Width (mm)		4.5	10.8	7.9	1.1
	Weight (g)		1.6	12.5	5.5	2.3
GYN (*G. nicholsi*)	Length (mm)	69	90.7	163.9	138.5	12.4
	Height (mm)		13.7	27.1	21.8	2.4
	Width (mm)		7.8	14.8	12.5	1.2
NOG (*G. gibberifrons*)	Length (mm)	43	275.0	364.0	321.9	20.6
	Height (mm)		41.8	67.7	53.8	6.8
	Width (mm)		51.2	74.9	61.7	6.4
NTO (*N. coatsi*)	Length (mm)	85	86.4	356.0	244.0	65.7
	Height (mm)		6.1	19.3	13.9	3.4
	Width (mm)		3.5	13.1	8.8	2.0

distribution with bimodal length distributions. Body lengths ranged from 86.4 mm to 356.0 mm, heights ranged from 6.1 mm to 19.3 mm, and widths ranged from 3.1 mm to 13.1 mm (Table 3; Figure 6).

3.4 Release ratios of dominant and important bycatch species for different bar spacing

Modelled release ratios for different species under various bar spacings are as follows: *C. gunnari* was 93.94%, 71.72%, 69.70%, 66.67%, and 66.67% in number, while 99.97%, 99.54%, 99.39%, 99.02%, and 99.02% in weight for 10 mm, 15 mm, 20 mm, 25 mm, and 30 mm bar spacings, respectively. *P. georgianus* was 53.99%, 52.15%, 34.36%, 30.06%, and 28.22% in number, while 99.95%, 99.85%, 98.18%, 97.68%, and 97.16% in weight for 10 mm, 15 mm, 20 mm, 25 mm, and 30 mm bar spacings, respectively. *C. aceratus* was 76.25% in number and 99.99 in weight for 10 mm bar spacing, while 73.55% in number and 99.1% in weight for bar spacings over 15 mm to 30 mm. *G. gibberifrons* was all 100% for bar spacings below 30 mm. *E. carlsbergi, G. nicholsi*, and *N. coatsi* were 1.25%, 97.10%, and 43.02% in number, while 2.89%, 99.38%, and 75.21% in weight for 10 mm bar spacing, and 0% for bar spacing larger than 15 mm for these three species (Table 4; Figure 7).

4 Discussion

4.1 The species composition of finfish bycatch in the krill fishery

The waters around the South Orkney Islands are a primary location for krill fishing in Subarea 48.2 of CCAMLR. Commercial krill trawling is concentrated in this area from December to March or April of the following year (Atkinson et al., 2008; Krafft et al., 2023). Bycatch levels have been observed to increase with the increase in krill catch (Kock et al., 2012; CCAMLR, 2022a). Krafft et al. (2023) reported that the bycatch ratio ranged from 0.1-0.3% and was dominated by finfish during the fishing season in Subareas 48.1, 48.2, and 48.3. The bycatch ratio differences in krill fisheries are possibly caused by seasonal and spatial variation (Kozlov et al., 1990; Krafft et al., 2023). The highest bycatch ratios were observed in February-March in Subarea 48.2 (Krafft et al., 2023). This subarea hosts a considerable proportion of high-Antarctic finfish species due to the influence of Weddell Sea water (Kock et al., 2000). Our study found that the finfish bycatch ratio ranged from 0-0.1% in this subarea during a two-month period.

Information on bycatch composition and mitigation by species is crucial for the responsible management of the krill fishery in an EBFM framework, including the impact of krill fishery on bycatch species. This study identified three dominant bycatch species (*C. gunnari*, *P. georgianus*, and *C. aceratus*) from the *Channichthyidae* family. Additionally, four important bycatch species were identified: *G. gibberifrons* from the *Nototheniidae* family, *E. carlsbergi* and *G. nicholsi* from the *Myctophidae* family, and *N. coatsi* from the *Paralepididae* family. Our results are consistent with previous studies that found the bycatch to be dominated by demersal species from the families *Nototheniidae* and *Channichthyidae*, pelagic species from the family *Myctophidae*, and bathypelagic species from the family *Paralepididae* in this area (Williams, 1985; Kock et al., 2000, 2012; Hill et al., 2007).

4.2 Bycatch difference between conventional trawling and continuous fishing

This study revealed that the finfish bycatch differed between conventional trawling and continuous fishing is most likely a result of gear differences, fished in different areas, and different depths (Jones et al., 2000; Collins et al., 2012). Conventional trawling takes

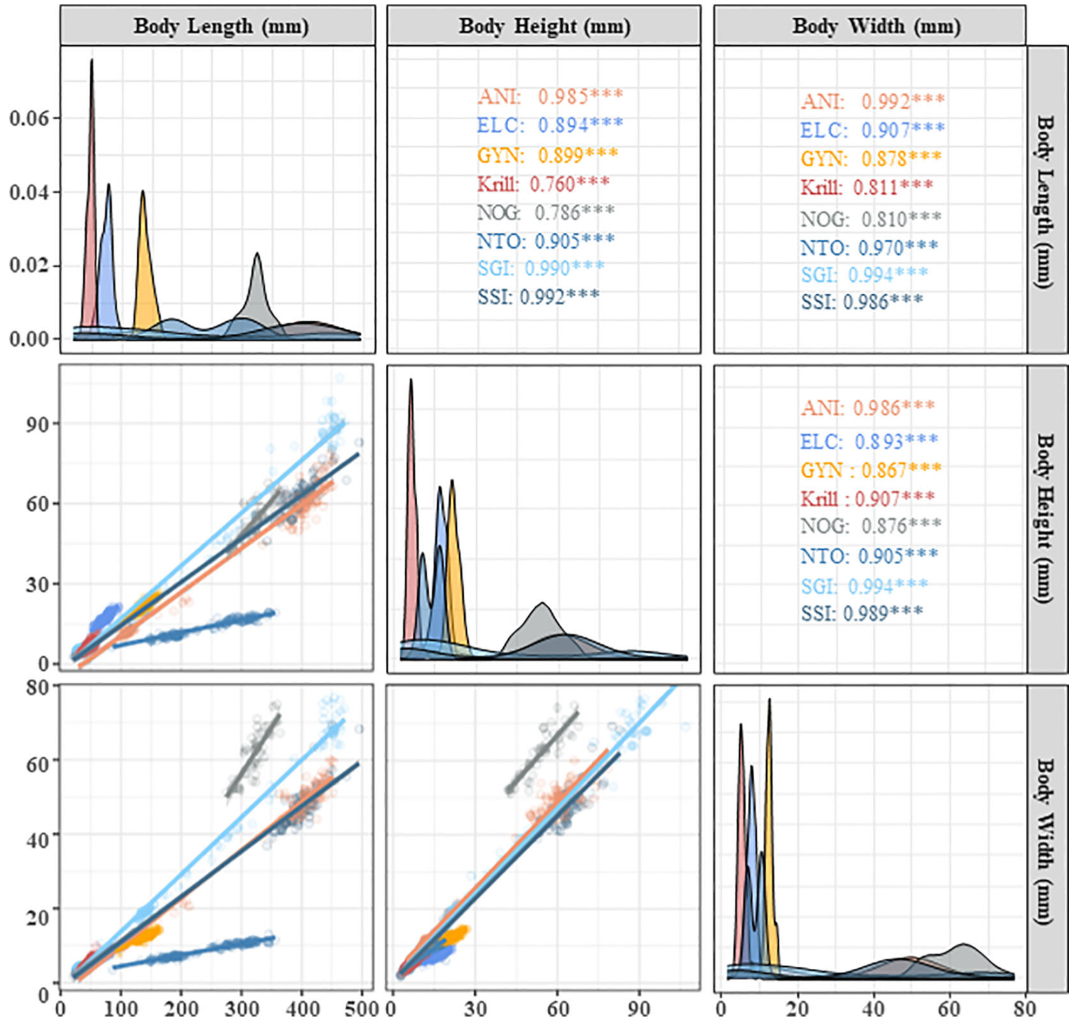

FIGURE 6
Length distributions and relationships of body height and width at length for krill and dominant and important bycatch species caught during krill trawls taken by F/V SHEN LAN in the waters of the South Orkney Islands from December 24, 2022, to February 20, 2023. Notes: The species names corresponding to the codes in the legend are *C. gunnari* (ANI), *P. georgianus* (SGI), *C. aceratus* (SSI), *E. carlsbergi* (ELC), *G. nicholsi* (GYN), *G. gibberifrons* (NOG), *N. coatsi* (NTO). The horizontal axis legend is located at the top. The vertical axis legend is located on the right side. Diagonal figures represent body length distribution. Scatter plot and linear fitting of the relationship between body length, height, and width at the bottom left corner of the diagonal figures. Pearson correlation coefficient and its significance between body length, height, and width are located at the upper right corner of the diagonal figures (*** - mean significance level<0.001).

place in the layer from the surface to depths of nearly 300 meters, predominantly in shelf areas. In comparison, continuous fishing was done in the layer shallower than 120 meters in a relatively deepwater area.

Our study found that except for *P. georgianus*, the demersal species (*C. gunnari*, *P. georgianus*, *C. aceratus*, and *G. gibberzfrons*) were dominant and important bycatch in the hauls of conventional trawling rather than continuous fishing (Kock et al., 2000, 2012; Jones et al., 2000). The specimens of the pelagic species *E. carlsbergi* were caught in the continuous fishery from the surface to depths of 100 meters in deepwater areas. In contrast, *G. nicholsi* were caught in conventional trawling at fishing depths around 100 meters in the shelf area. Those results are consistent with previous studies. *E. carlsbergi* tends to live in deepwater and move up to the epipelagic zone (50 to 200 m) during the spring and summer seasons (Filin et al., 1990; Kozlov et al., 1990; Everson et al., 1992; Kozlov, 1995). In comparison, the pelagic stock of *G. nicholsi* comprises juveniles and sub-adults living in offshore waters (Linkowski, 1985; Saunders and Tarling, 2018).

Additionally, our study found that *N. coatsi* were caught at almost all fishing depths. This result is consistent with previous studies that *N. coatsi* has a predominantly oceanic distribution where it is found from the surface to depths of more than 2000 meters (Williams, 1985; Torres and Somero, 1988; Gon and Heemstra, 1990; Hoddell et al., 2000), although specimen larger than 55 mm are mainly caught in continental slope areas (Hoddell et al., 2000).

TABLE 4 Release ratios for different bar spacing options of exclusion devices for dominant and important bycatch species during the study period carried out by F/V SHEN LAN in the waters of the South Orkney Islands.

Release ratios in	Bar spacing (mm)	Release ratio (%)						
		C. gunnari	*P. georgianus*	*C. aceratus*	*G. gibberifrons*	*E. carlsbergi*	*G. nicholsi*	*N. coatsi*
number	10	93.94	53.99	76.25	100	1.25	97.10	43.02
	15	71.72	52.15	73.75	100	0	0	0
	20	69.70	34.36	73.75	100	0	0	0
	25	66.67	30.06	73.75	100	0	0	0
	30	66.67	28.22	73.75	100	0	0	0
weight	10	99.97	99.95	99.99	100	2.89	99.38	75.21
	15	99.54	99.85	99.91	100	0	0	0
	20	99.39	98.18	99.91	100	0	0	0
	25	99.02	97.68	99.91	100	0	0	0
	30	99.02	97.16	99.91	100	0	0	0

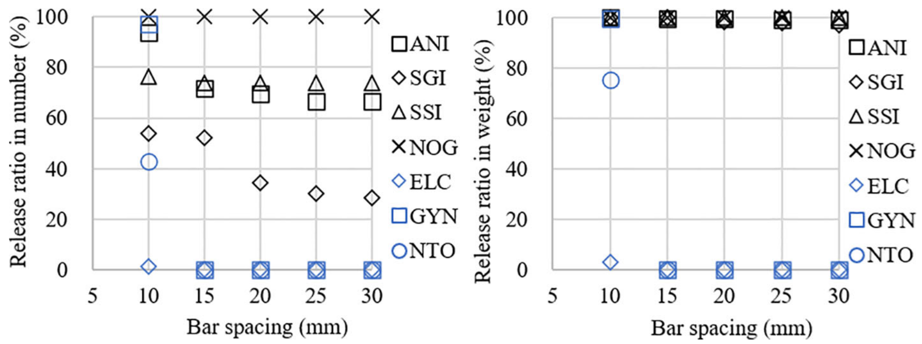

FIGURE 7
Modelled release ratios in number (left) and weight (right) of the bycatch exclusion device for bar spacings of 10, 15, 20, 25, and 30 mm. Calculations are made for dominant and important bycatch species *C. gunnari* (ANI), *P. georgianus* (SGI), *C. aceratus* (SSI), *E. carlsbergi* (ELC), *G. nicholsi* (GYN), *G. gibberifrons* (NOG), and *N. coatsi* (NTO) during the study period carried out by F/V SHEN LAN in the waters of the South Orkney Islands.

4.3 Bar spacing of size-selective grids for releasing fishing vulnerable bycatch species

Understanding the species composition and the physical characteristics of the finfish bycatch is essential to design effective exclusion devices for the krill trawl fishery. These devices are meant to release the finfish bycatch while retaining the targeted krill. Broadhurst et al. (2018) suggested that the bar spacing for reducing larger bycatch species can be fixed at a size approaching the maximum body width of the targeted species. Araya-Schmidt et al. (2023) found that using a Nordmøre grid with a 17 mm or 15 mm bar spacing effectively reduced redfish bycatch without significant loss of specimens of the target species Northern shrimp with carapace lengths up to 30 mm and carapace widths up to 15 mm. This study investigation found that the target species, krill, had a unimodal size distribution, and the maximum body width was 9.92 mm in the collected specimens. Therefore, the bar spacing should be no less than 10 mm.

We modelled release ratios solely based on morphometric measurements of dominant bycatch species (*C. gunnari*, *P. georgianus*, and *C. aceratus*) and important bycatch species (*E. carlsbergi*, *G. nicholsi*, and *G. gibberifrons*) for different bar spacing. A 10 mm bar spacing can release a significant amount of dominant bycatch species (93.94% of *C. gunnari*, 53.99% of *P. georgianus*, and 76.25% of *C. aceratus*) and important bycatch species (100% of *G. gibberifrons*) according to the body size composition in our investigation. In comparison, a 15 mm bar spacing will retain more juveniles of the dominant bycatch species (28.28% of *C. gunnari*, 47.85% of *P. georgianus*, and 26.25% of *C. aceratus*) and almost all important bycatch species *E. carlsbergi*, *G. nicholsi*, and *N. coatsi*. In future sea trials of a sorting grid, we recommend to test a bar spacing of 10 mm. If the trials demonstrate loss of krill, particularly at high catch rates of krill, a wider bar spacing of 15 mm should be tested. This will result in higher bycatch of less vulnerable species (i.e., *E. carlsbergi, G. nicholsi*, and *N. coatsi*).

5 Conclusions

This study reveals generally low bycatch rates in the krill fishery, but three dominant and vulnerable species (*C. gunnari*, *P. georgianus*, and *C. aceratus*) may suffer from overexploitation of krill fishery. We measured morphometric data (particularly body width) of krill and finfish bycatch, which is crucial to model release ratios of bycatch reduction devices for these species. Calculations suggest that a large fraction of dominant and vulnerable species can be excluded using a grid type BRD within a 15 mm bar spacing.

Data availability statement

The original contributions presented in the study are included in the article/Supplementary Material. Further inquiries can be directed to the corresponding authors.

Ethics statement

The manuscript presents research on animals that do not require ethical approval for their study.

Author contributions

ZW: Data curation, Investigation, Visualization, Writing – original draft, Writing – review & editing, Formal analysis, Funding acquisition. SM: Writing – review & editing, Conceptualization, Formal analysis, Methodology. YW: Writing – review & editing, Investigation. LW: Writing – review & editing, Funding acquisition, Project administration, Supervision.

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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.

Publisher's note

Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fmars.2024.1325120/full#supplementary-material

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Appendix 1

Fishing information on each haul of finfish bycatch was observed in the krill trawl onboard F/V SHEN LAN in the waters of South Orkney Islands (Notes: The fishing latitude, longitude, and depth are the median of the starting and ending fishing latitudes, longitudes, and depths; The bycatch ratio is by weight).

Fishing method	Start fishing				End fishing				Fishing Latitude (°S)	Fishing Longitude (°W)	Fishing depth (m)	CPUE (t/h)	Bycatch ratio (%)
	Latitude (°S)	Longitude (°W)	Bottom depth (m)	Fishing depth (m)	Latitude (°S)	Longitude (°W)	Bottom depth (m)	Fishing depth (m)					
Continuous fishing	60.31	45.97	385	26	60.27	45.99	320	62	60.29	45.98	44.0	5.02	0.0018
	60.30	46.08	465	18	60.35	46.05	480	35	60.32	46.07	26.5	8.25	0.0006
	60.06	47.28	2473	14	60.06	47.18	2253	10	60.06	47.23	12.0	9.06	0.0001
	60.03	47.30	2100	29	60.03	47.37	2183	31	60.03	47.34	30.0	3.53	0.0002
	60.08	47.34	2200	41	60.04	47.33	2200	30	60.06	47.33	35.5	6.07	0.0013
	59.99	47.38	2180	22	59.96	47.39	2800	24	59.98	47.39	23.0	4.90	0.0011
	59.98	47.25	2800	28	59.99	47.35	2800	29	59.98	47.30	28.5	4.57	0.0003
	60.07	47.49	2800	22	60.12	47.46	1780	31	60.10	47.47	26.5	6.80	0.0010
	60.17	47.46	1060	37	60.22	47.52	1078	25	60.20	47.49	31.0	20.84	0.0006
	60.05	47.14	2620	35	60.08	47.23	1910	35	60.07	47.19	35.0	7.95	0.0055
	60.04	46.91	2440	30	60.03	46.95	2585	28	60.03	46.93	29.0	2.48	0.0093
	60.01	47.11	3185	21	59.97	47.20	4075	38	59.99	47.16	29.5	3.68	0.0010
	60.33	46.34	3200	45	60.32	46.34	3225	39	60.33	46.34	42.0	28.85	0.0002
	60.31	45.94	1310	21	60.32	45.95	1138	52	60.32	45.95	36.5	9.81	0.0006
	60.33	46.28	3052	14	60.34	46.24	2945	23	60.34	46.26	18.5	21.45	0.0001
Conventional trawling	60.44	45.89	172	5	60.43	46.09	172	5	60.44	45.99	5.0	11.75	0.0000
	60.42	45.89	412	10	60.42	46.01	412	10	60.42	45.95	10.0	22.02	0.0021
	60.38	46.07	1400	45	60.38	46.11	1400	45	60.38	46.09	45.0	11.99	0.0026
	60.35	46.66	860	40	60.36	46.70	860	40	60.35	46.68	40.0	13.78	0.0012
	60.38	46.73	381	25	60.49	46.64	381	15	60.44	46.69	20.0	7.28	0.0027
	60.38	46.10	1973	42	60.36	46.14	1973	42	60.37	46.12	42.0	11.54	0.0030
	60.41	46.08	1530	43	60.39	46.16	1530	43	60.40	46.12	43.0	23.03	0.0000
	60.42	46.10	760	42	60.42	46.14	760	42	60.42	46.12	42.0	17.22	0.0011
	60.37	46.27	1800	66	60.41	46.23	1800	66	60.39	46.25	66.0	39.17	0.0001
	60.43	46.16	1530	70	60.44	46.02	1530	70	60.43	46.09	70.0	52.82	0.0000
	60.42	45.93	201	10	60.42	45.77	201	10	60.42	45.85	10.0	14.89	0.0081
	60.37	46.20	2450	82	60.37	46.12	2450	82	60.37	46.16	82.0	24.00	0.0002
	60.41	46.22	1345	55	60.40	46.13	1345	55	60.40	46.18	55.0	11.45	0.0029
	60.39	46.23	1915	130	60.41	46.18	1915	130	60.40	46.20	130.0	45.89	0.0006
	60.51	46.10	400	30	60.52	46.06	400	30	60.52	46.08	30.0	83.14	0.0003
	60.55	44.93	345	230	60.58	44.98	345	230	60.56	44.95	230.0	23.44	0.0037
	60.57	44.98	395	288	60.55	44.92	395	288	60.56	44.95	288.0	8.63	0.0054
	60.46	45.35	420	210	60.45	45.39	420	210	60.46	45.37	210.0	39.03	0.0192
	60.44	45.69	260	176	60.44	45.62	260	176	60.44	45.66	176.0	40.05	0.0331
	60.43	45.70	260	20	60.42	45.73	260	20	60.43	45.72	20.0	18.39	0.0033
	60.50	45.24	307	140	60.49	45.29	307	140	60.49	45.27	140.0	22.66	0.1002

(Continued)

Continued

Fishing method	Start fishing				End fishing				Fishing Latitude (°S)	Fishing Longitude (°W)	Fishing depth (m)	CPUE (t/h)	Bycatch ratio (%)
	Latitude (°S)	Longitude (°W)	Bottom depth (m)	Fishing depth (m)	Latitude (°S)	Longitude (°W)	Bottom depth (m)	Fishing depth (m)					
	60.45	45.24	450	160	60.48	45.29	450	160	60.46	45.26	160.0	10.02	0.0872
	60.50	45.17	307	180	60.49	45.11	307	180	60.50	45.14	180.0	8.06	0.0198
	60.46	45.18	410	120	60.45	45.25	410	120	60.45	45.22	120.0	12.64	0.0574
	60.47	45.27	312	95	60.46	45.19	312	95	60.46	45.23	95.0	19.51	0.0362
	60.62	44.98	280	200	60.54	45.00	280	200	60.58	44.99	200.0	12.04	0.0060
	60.54	45.09	306	210	60.55	44.99	306	210	60.54	45.04	210.0	19.39	0.0076
	60.55	44.95	339	210	60.58	44.96	339	210	60.56	44.95	210.0	45.71	0.0014
	60.51	44.92	397	120	60.54	44.93	397	120	60.52	44.93	120.0	67.39	0.0021
	60.55	44.94	340	26	60.51	44.95	340	26	60.53	44.94	26.0	35.63	0.0004
	60.44	45.76	180	100	60.44	45.71	180	100	60.44	45.73	100.0	48.14	0.0575
	60.41	45.79	306	110	60.43	45.78	306	110	60.42	45.78	110.0	7.02	0.0419
	60.54	46.10	178	93	60.52	46.08	178	93	60.53	46.09	93.0	50.27	0.0000
	60.53	46.10	494	115	60.52	46.09	494	115	60.52	46.09	115.0	74.34	0.0000
	60.43	45.88	222	130	60.41	45.92	222	130	60.42	45.90	130.0	75.27	0.0027
	60.42	45.97	214	40	60.39	46.00	214	40	60.40	45.99	40.0	21.42	0.0225
	60.43	45.65	279	190	60.43	45.73	279	190	60.43	45.69	190.0	40.35	0.0028
	60.50	45.31	258	162	60.46	45.42	258	162	60.48	45.36	162.0	14.72	0.0027
	60.53	45.28	258	110	60.48	45.33	258	110	60.51	45.31	110.0	41.35	0.0003
	60.48	45.41	242	156	60.48	45.46	242	156	60.48	45.43	156.0	61.92	0.0214
	60.46	46.01	235	100	60.45	46.12	235	100	60.45	46.06	100.0	17.76	0.0135