Journal of
Marine Science and Engineering

MDPI

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The Escape Intensity and Its Influencing Factors in Antarctic Krill (*Euphausia superba*) Passing through Large Mesh at the Front End of a Commercial Trawl

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Abstract: The purpose of this study was to comprehend the escape intensity and its influencing factors in Antarctic krill (*Euphausia superba*) that escaped through large mesh located at the front end of commercial trawl nets. Two pocket nets were employed to collect escaped krill that passed through the mesh opening in the first section (400 mm mesh size, without liner) and second section (16 mm mesh size liner) of the trawl body. The results show that krill escape primarily took place in the first section of the trawl body. Meanwhile, there was almost no krill escape observed in the second section of the trawl body, primarily attributable to the presence of a 16 mm mesh size liner. In terms of body length composition, the average PSI (percentage similarity index) was 67.31 (95% CI: 61.86–72.87) for krill from the pocket net on the larger mesh part and the codend. In addition, the PSI was significantly different ($p < 0.05$) between the day (60.96, 95% CI: 55.68–66.71) and night (83.62, 95% CI: 76.80–89.46). The escape intensity of krill ranged from 20.83 to 213.13 $g \cdot m^{-2}$ per ton per hour in the area at the front end of trawl body, with a mean value of 76.52 (95% CI: 55.22–101.09) $g \cdot m^{-2}$ per ton per hour during the daytime, and 144.66 (95% CI: 110.44–180.03) $g \cdot m^{-2}$ per ton per hour at night. These results indicate that krill can see and avoid contacting the netting easily during the day, particularly for larger individuals. This provides insight into the design of krill trawls, specifically on the arrangement of liners, which should be integrated from the front part of the trawl body.

Keywords: trawl; pocket net; liner netting; percent similarity index; diurnal pattern

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Citation: Wang, Z.; Wang, L.; Wang, Y.; Tang, H.; Xu, L. The Escape Intensity and Its Influencing Factors in Antarctic Krill (*Euphausia superba*) Passing through Large Mesh at the Front End of a Commercial Trawl. *J. Mar. Sci. Eng.* **2023**, *11*, 2370. https://doi.org/10.3390/jmse11122370

Academic Editor: Sang Heon Lee

Received: 29 October 2023
Revised: 3 December 2023
Accepted: 13 December 2023
Published: 15 December 2023

1. Introduction

Antarctic krill (*Euphausia superba*) plays a crucial role as a keystone species within the Southern Ocean ecosystem. Its estimated biomass is approximately 100 million tons [1]. Furthermore, it is the primary target of commercial trawl fisheries in the Southern Ocean, with recent landings reaching approximately 400,000 tons [2].

Currently, commercial krill trawls commonly feature low tapered constructions with small-mesh liners fitted in the trawl body and the codend to reduce catch loss through mesh openings [3]. For liners, there are two strategies for the arrangement and mesh size of liners. One strategy is fitting small mesh (16 mm) liners that almost cover the whole trawl to minimize catch loss, such as the pelagic otter trawl used by the Chinese trawler 'Longteng' [4] and the pelagic beam trawl used by the Norwegian trawlers 'Saga Sea' and

'Antarctic Sea' [5,6]. The other strategy involves segmented degrading of the mesh size of the liner netting, starting from the front or middle of the trawl. For example, the pelagic otter trawl used by the Korean trawler 'Sejong' starts from the second section of the trawl body with 40 mm (2nd–3rd sections), then decreases to 30 mm (4th section), 25 mm (5th section), 20 mm (6th section), and finally to a 15 mm mesh size at the codend [7]. The liner netting of the trawl used by the Chinese trawler 'Furonghai' starts from the sixth section with 30 mm (6th–7th sections), to 25 mm (8th–9th sections), then to 20 mm (10th–11th sections) of the trawl body, and finally to a 15 mm mesh size at the codend [8].

Krill are generally regarded as planktonic organisms, and like other smaller invertebrates, they tend to display a more limited response to the stimuli presented by netting [9–11]. The size selection resembles a sieving process, with individuals meeting the netting frequently in random orientations [12–16]. However, krill also display the ability to move horizontally and vertically in the water column at high speeds for limited periods. These different arrangements and mesh sizes of liners result in various fishing performances, resulting in krill escaping through mesh openings and retention in the codend. Czubek [17] found that krill escaped through 90 mm mesh at the front part of the trawl body and through 12 mm mesh bars of the liner at the rear part of the trawl body and the codend. Herrmann et al. [18] found that the trawl body contributed to size selection, and a 16 mm mesh size liner would affect the retention of krill smaller than 32 mm in body length. Wang et al. [19] found that catch patterns for krill varied from different commercial trawls in similar spatio-temporal fishing grounds. Substantial numbers of krill below 30 mm were caught in a trawl fitted with a 16 mm mesh size liner starting from the front section of the trawl body. Meanwhile, very few were caught in the trawl using segmented decreasing mesh sizes of liners, as used by 'Furonghai'.

Therefore, it is crucial to have detailed knowledge of the escaped krill during fishing operations to enhance trawl design. Assessing the animals that escape from the front part of a trawl can be difficult. Matsushita et al. [20] applied pocket nets (also called recapture nets, cover nets, or collection bags) to determine where walleye pollock (*Theragra chalcogramma*) escaped from a midwater trawl. Williams et al. [21,22] also applied pocket nets to document the escape of walleye pollock from the body of a midwater survey trawl. They found that the walleye pollock was closer to the netting panel, and consequently there were more escape events at night than during the day, particularly for smaller fish. Therefore, we utilized the pocket net method to examine the liner's impact on catch loss, and to evaluate the intensity of krill that escaped through the larger mesh at the front end of the trawl.

2. Materials and Methods

2.1. Sea Trials

Sea trials were conducted onboard a Chinese commercial trawler from 28 March to 5 April 2019. In total, 25 hauls for sea trials were towed in the area between the Antarctic Peninsula and the South Shetland Islands. The R (version 3.6.1) package 'maps' was used to draw the sample site map of these hauls (Figure 1). Additionally, a wireless net monitor 'MARPORT M4' was installed on the top panel of the trawl to document the fishing depth.

The commercial trawl is a four-panel door-operated pelagic trawl. The doors are the type 'SMA-2800 × 4650', which was designed by BM International Co., Ltd. (Busan, Republic of Korea). The main dimensions of this trawl include a stretched perimeter of 300 m at the mouth and a total stretched length of 132.8 m. The wing is 20 m long with a mesh size of 400 mm. The trawl body is 88.8 m long, and evenly divided into 11 sections. The liner (16 mm mesh size) was equipped from the second section to the end of the trawl body. Two pocket nets were bound on the outside of the netting to collect all krill escapees that passed through the mesh opening. One was located at the rear of the first section (400 mm mesh size, no liner) at around 10 m from the headline; the other was located at the front of the second section (200 mm mesh size, with a 16 mm liner) at around 12 m from the headline. The pocket nets have a steel opening frame of 0.2 m × 0.2 m to keep the mouth from opening, and the main frame was covered by a 5 mm mesh size netting (Figure 2).

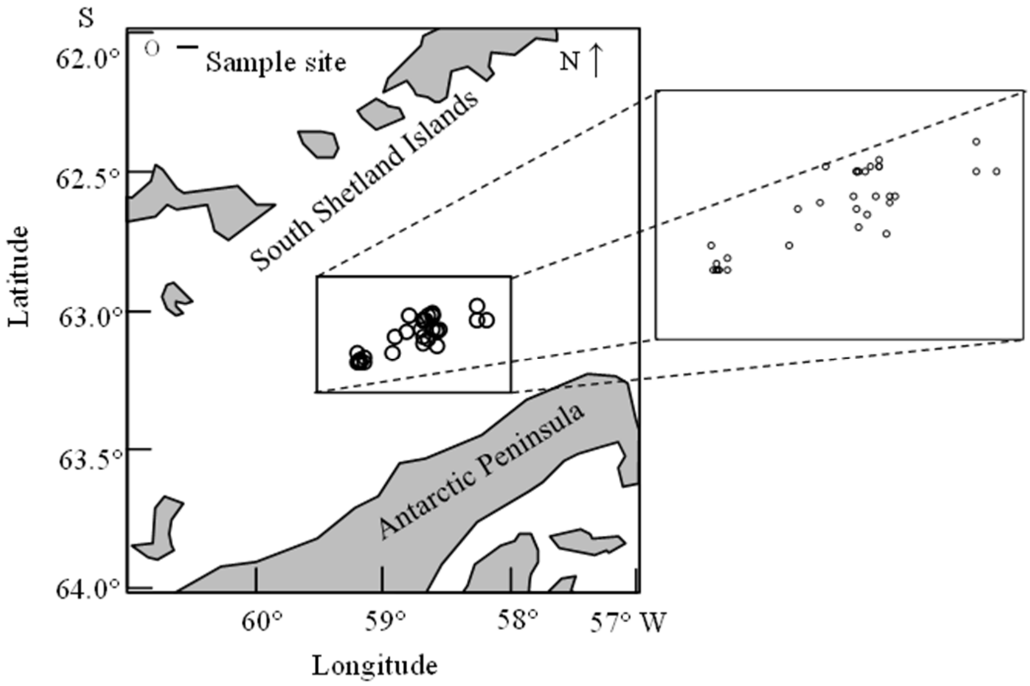

Figure 1. Sample sites of 25 hauls that were towed in the area between the Antarctic Peninsula and the South Shetland Islands (Note: the right map Latitude is 62.8 S–63.3 S; Longitude is 58 W–59.5 W).

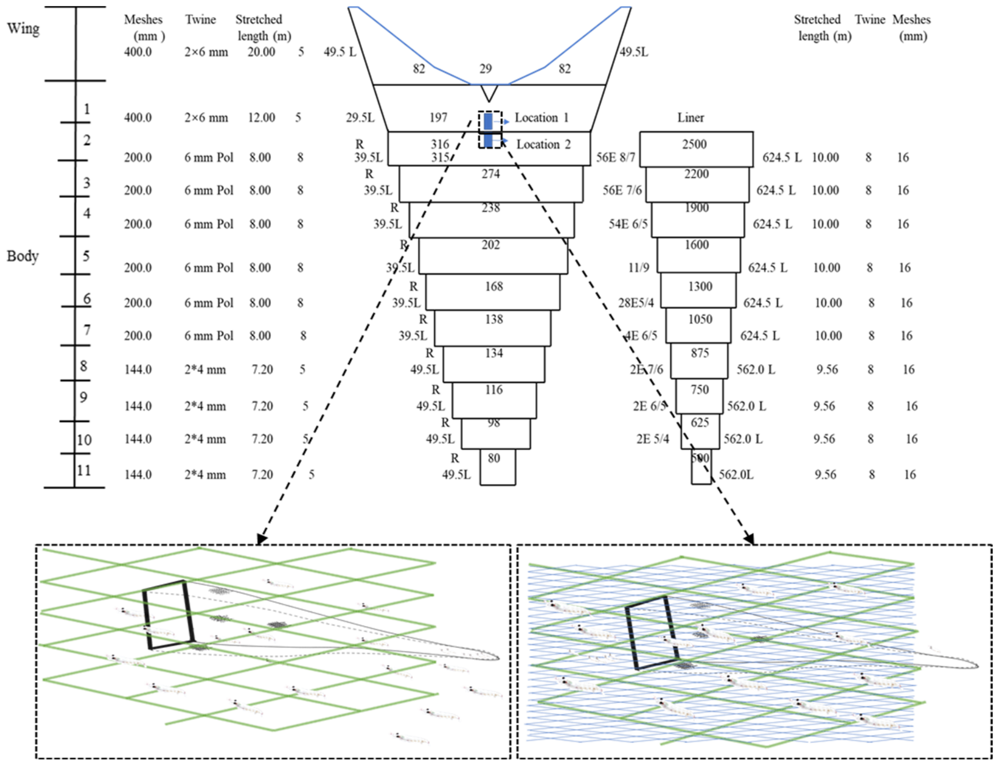

Figure 2. The parameters of the trawl, including starting points of the liners and the location of the pocket nets at the top panel of the trawl; Partial schematic diagram of the pocket net (with black steel utilized to keep the mouth open) used to collect escaped krill passing through the large mesh (2a = 400 mm, green color) at location 1 (bottom left), and the liner netting (2a = 16 mm, blue color) at location 2 (bottom right).

2.2. Sampling and Measurement

We used a scale (range = 1000 g, resolution = 5 g) to measure the weight of the krill retained in the pocket nets. For each haul, 200 individual krill were sampled from both the pocket nets and the codend, respectively. Otherwise, all krill were sampled if the total number of krill in the pocket net was less than 200 individuals. In addition, we used a plastic package measurement panel (length = 350 mm, width = 250 mm, resolution = 1 mm) to measure the body length of each krill from the front of the eye to the tip of the telson, based on the CCAMLR standard protocols [23].

2.3. Data Analysis

2.3.1. Percentage Similarity Index

Krill body length was grouped into 5 mm intervals. The median body length of each group was used as the characteristic length: 17.5 (<20), 22.5 (20–24), 27.5 (25–29), 32.5 (30–34), 37.5 (35–39), 42.5 (40–44), 47.5 (45–49), and 52.5 (≥50) mm. We applied the percentage similarity index (PSI) [24] to evaluate the similarity of the body length composition of krill between the pocket net and the codend in the same haul. The formula for PSI is as follows:

$$PSI_i = [1 - 0.5\sum_{k=1}^{n} abs(P_{ika} - P_{ikc})] * 100 \quad (1)$$

where PSI_i is the similarity of the body length composition of krill between the pocket net and the codend of the i-th haul; P_{ika} is the proportion of krill whose body length falls in group 'k' of the i-th haul in the pocket net; P_{ikc} is the proportion of krill whose body length falls in group 'k' of the i-th haul in the codend; and n is the number of the body length group.

Generally, Newman [24] suggested that body length compositions are similar when the PSI $\geq$ 80. We applied Microsoft Excel (2016) to calculate the PSI of each haul, and IBM SPSS Statistics (version 20.0) to process normality tests and differences analysis. Unless otherwise specified, the data are expressed as means within the 95% Confidence Interval (95% CI).

2.3.2. Escape Intensity of Krill and Its Influencing Factors

Krill, as planktonic organisms, have weak swimming abilities. This affects the catch and towing time, impacting the weight of krill that escape through the larger mesh netting = at the front part of the trawl body [9–11]. Therefore, we standardized the weight of the escaped krill in the pocket (m_p) using nominal CPUE. Thus, the escape intensity of krill (m_s) near the pocket net area is expressed as:

$$m_s = \frac{m_p}{CPUE} * \frac{1}{A_p} \quad (2)$$

where Ap is the pocket net opening square.

The nominal $CPUE$ is calculated based on the catch (m_c) and towing time (t):

$$CPUE = \frac{m_c}{t} \quad (3)$$

The escape intensity of krill (m_s) was utilized as the response variable. Explanatory factors were the diurnal cycle (day-night), the weighted mean body length of the krill in the codend, and the fishing depth. The Generalized Additive Model (GAM) [25–27] is expressed as:

$$g\ (m_s) = Diurnal + s\ (Weighted\ mean\ body\ length\ of\ krill\ in\ codend) + s\ (Fishing\ depth) + \varepsilon \quad (4)$$

In Formula (4), ε is the error term, and s is the natural cube spline smoother.

We applied the 'mgcv' and 'condvis' packages [28] to conduct and visualize the GAM analysis, using R (x64 version 3.6.1) software. Then, we utilized 'Adobe Acrobat Pro DC' for image post-processing to display day and night data graphs together. We chose the final models using back selection, based on Akaike's Information Criterion (AIC), to evaluate each of the variables removed from the base model. We obtained the 95% CI of the fitted values for the escape intensity of krill using bootstrapping. Additionally, we applied estimated degrees of freedom (EDF) to determine whether the selected factor was non-linearly associated with the response variables.

3. Results

3.1. Weight of Krill Collected in the Pocket Net

During the cruise, there were only a few krill collected in the pocket net located at the second section (location 2) of the trawl body, with a 16 mm mesh size liner. In contrast, a large number of krill were collected in the pocket net located at the back of the first section (location 1) without liner netting. In 25 hauls, the weight of the krill collected in the pocket net at location 1 ranged from 45 g to 385 g, with a mean weight of 125.92 (95% CI: 96.41–162.00) g (Table 1). The dominant range was from 50 g to 149 g (Figure 3).

Table 1. Statistical of the weight of krill was collected in the pocket net at location 1.

Statistics			Bootstrap [a]			
			Deviation	Std. Error	95% Confidence Interval	
					Lower Limit	Upper Limit
Number of Hauls		**25**			**25**	**25**
Weight (g)	Minimum	45				
	Maximum	385				
	Mean	125.92	0.44	16.90	96.41	162.00
	Std. Dev	82.94	−3.84	17.50	46.12	111.22

Note: [a] Based on 1000 bootstrap samples.

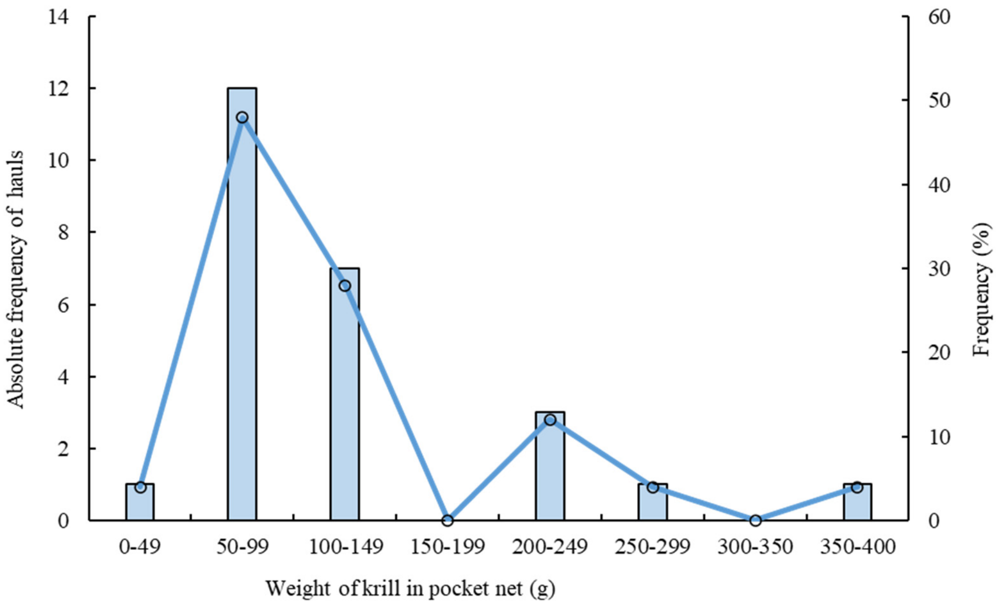

Figure 3. The absolute frequency of hauls (left vertical ordinate) and the frequency (right vertical ordinate) for the weight of the krill in the pocket net at location 1.

3.2. Body Length Composition and PSI of Krill between the Pocket Net and the Codend

In the pocket net, the dominant body length group of krill was 25–30 mm. The frequency during the day-time hauls was 63.9% (95% CI: 59.1–68.8%), which was higher than the night-time hauls at 52.1% (95% CI: 39.9–63.2%). For the body length group over 30 mm, the day-time hauls were lower than the night-time hauls, except for the body length group over 50 mm. While in the codend, the dominant body length group of krill was 25–40 mm. For the body length group of 25–30 mm, the frequency of krill during the day-time hauls was 26.4% (95% CI: 20.9–32.6%), which was lower than the night-time hauls at 42.2% (95% CI: 25.6–59.0%). Meanwhile, for the body length group over 30 mm, the day-time hauls were higher than the night-time hauls, except for the 35–40 mm group (Table 2, Figure 4).

Table 2. The body length frequency of the krill sampled from the pocket net and the codend.

Group		**Number of Hauls**	**Median of Body Length Class**					
			27.5 mm	**32.5 mm**	**37.5 mm**	**42.5 mm**	**47.5 mm**	**52.5 mm**
Pocket net	Day	18	63.9 (59.1–68.8) [a]	23.2 (20.4–25.6) [a]	8.2 (5.9–10.8) [a]	2.9 (2.1–3.9) [a]	1.3 (0.6–2.3) [a]	0.5 (0.1–1.3) [f]
	Night	7	52.1 (39.9–63.2) [b]	26.6 (22.0–31.0) [c]	13.3 (9.2–18.0) [c]	5.6 (2.1–10.3) [e]	2.1 (0.8–3.6) [d]	0.4 (0.1–1.0) [g]
	Sig.		0.141	0.178	0.034 *	0.745	0.326	0.745
Codend	Day	18	26.4 (20.9–32.6) [a]	26.9 (22.9–31.1) [a]	18.6 (16.4–20.9) [a]	15.4 (12.6–18.3) [a]	9.6 (7.2–12.3) [a]	3.4 (1.5–5.8) [a]
	Night	7	42.2 (25.6–59.0) [b]	24.5 (19.2–29.0) [b]	19.0 (11.8–26.0) [b]	8.7 (4.1–14.5) [b]	4.7 (2.0–7.7) [b]	0.9 (0.4–1.4) [c]
	Sig.		0.11	0.836	0.657	0.021 *	0.055	0.11

Notes: [a] Based on 1000 bootstrap samples. [b] Based on 996 samples. [c] Based on 994 samples. [d] Based on 993 samples. [e] Based on 991 samples. [f] Based on 988 samples. [g] Based on 883 samples. Sig. Mann-Whitney U test, '*' 0.05 level.

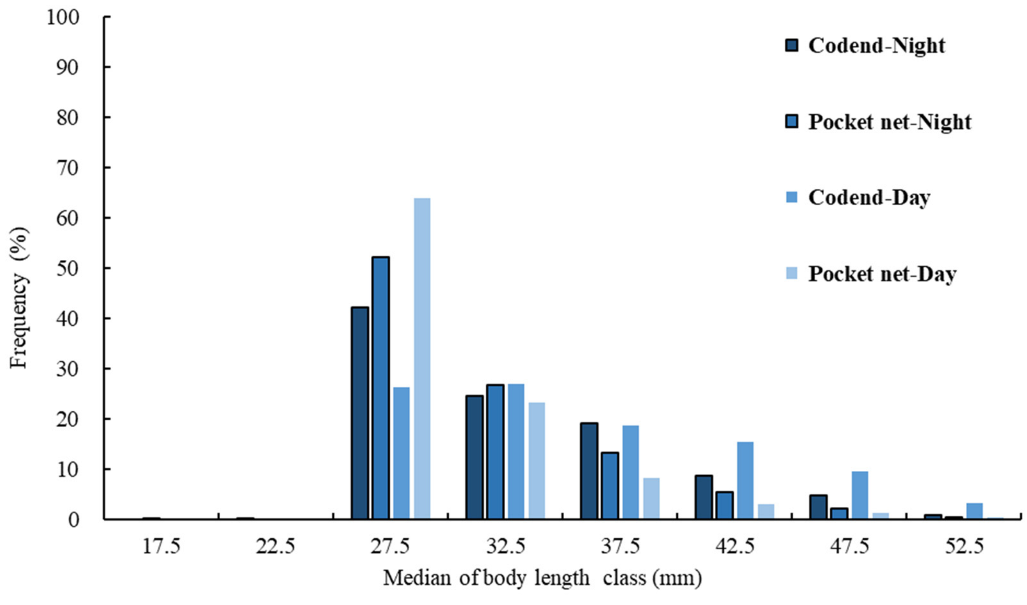

Figure 4. The body length frequency of the krill collected in the pocket net and the codend during the day and night.

The mean PSI of 25 hauls was 67.31 (95% CI: 61.86–72.87), based on the body length composition of krill between the pocket net and the codend. In addition, the PSI value had a significant difference ($p < 0.05$) between day and night. During the day, the mean PSI value was 60.96 (95% CI: 55.68–66.71), and only one eighteenth (5.56%) of hauls had a PSI value higher than 80. At night, the mean PSI value was 83.62 (95% CI: 76.80–89.46), and six sevenths (85.71%) of hauls had a PSI value higher than 80, with the PSI of some hauls reaching up over 90 (Table 3, Figure 5).

Table 3. The PSI of the body length composition for krill between the pocket net and the codend.

Group	Number of Hauls	Mean Value (mm)	Std. Dev (mm)	Sig.
PSI	25	67.31 (61.86–72.87) [a]	15.15 (11.49–18.02) [a]	
PSI-Day	18 (1)	60.96 (55.68–66.71) [a]	11.98 (7.19–15.76) [a]	0.000 *
PSI-Night	7 (6)	83.62 (76.80–89.46) [b]	9.00 (1.21–12.40) [b]	

Notes: In the 'Number of Hauls' column, the number in brackets means the number of hauls in which the PSI value was higher than 80. [a] The 95% confidence intervals in brackets in the Mean and Standard Deviation columns were based on 1000 bootstrap samples. [b] Based on 995 samples. Sig. Mann-Whitney U test, '*' 0.05 level.

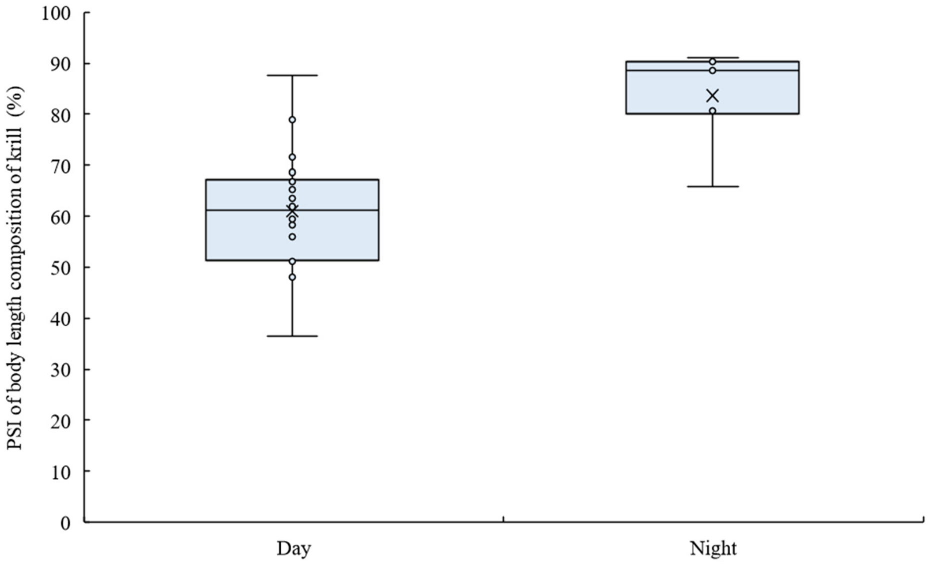

Figure 5. The PSI of the body length composition for krill from the pocket net and the codend between the day and night (Note: The cross line is the mean value mark; The dots are value points).

3.3. Escape Intensity of Krill and Its Influencing Factors

The escape intensity of krill at location 1 ranged from 20.83 to 213.13 g·m^{-2} per ton per hour, with a mean value of 95.60 (95% CI: 74.53–117.70) g·m^{-2} per ton per hour (Table 4). According to the GAM analysis, the diurnal cycle (day-night) had a significant effect on the escape intensity of krill ($p < 0.05$). Moreover, the model containing all of these factors had the smallest AIC value and was retained as the final model. The results indicate that the weighted mean body length of the krill in the codend and fishing depth had a nonlinear relationship (EDF $\neq$ 1) with the weight of the krill in the pocket net (Table 5). The mean value of escape intensity of the krill during the day (76.52, 95% CI: 55.22–101.09 g·m^{-2} per ton per hour) was lower than that at night (144.66, 95% CI: 110.44–180.03 g·m^{-2} per ton per hour). Moreover, the escape intensity of krill decreased first and then increased with the increase of the weighted mean body length of the krill in the codend. Additionally, the escape intensity of krill decreased with the increase of fishing depth (Figure 6).

Table 4. Descriptive statistics for the escape intensity (g.m-2 per ton per hour) of the krill at location 1.

Statistics			Bootstrap [a]			
			Deviation	Std. Error	95% Confidence Interval	
					Lower Limit	Upper Limit
Total	Number of Hauls	25			25	25
	Minimum	20.83				
	Maximum	213.13				
	Mean	95.60	−0.48	11.41	74.53	117.70
	Std. Dev	59.81	−1.89	6.23	45.07	69.60

Table 4. *Cont.*

Statistics			Bootstrap [a]			
			Deviation	Std. Error	95% Confidence Interval	
					Lower Limit	Upper Limit
Day	Number of Hauls	18			18	18
	Minimum	20.83				
	Maximum	180.56				
	Mean	76.53	0.39	12.05	55.22	101.09
Night	Std. Dev	52.76	−1.90	7.41	34.42	63.66
	Number of Hauls	7			7	7
	Minimum	87.86				
	Maximum	213.13				
	Mean	144.66	−0.44	17.86	110.44	180.03
	Std. Dev	50.22	−4.95	9.30	23.89	60.41

Note: [a] Based on 1000 bootstrap samples.

Table 5. Summary results of the 'GAM = escape intensity of krill and its influencing factors'.

Variable	Estimate	Std. Error	t Value	Pr(>|t|)	AIC
(Intercept)	73.77	12.63	5.84	1.13×10^{-5} ***	267.35
Diurnal (day-night)	77.98	32.09	2.43	0.02 *	271.93
	EDF	**Ref. df**	**F**	***p*-Value**	
Weighted mean body length of krill in codend (mm)	1.72	1.92	3.40	0.09	270.43
Fishing depth (m)	1.74	2.14	1.52	0.26	268.62

Notes: Signif. codes: 0 '***' 0.001 '*' 0.05 '.' 0.1. The AIC value, referring to removing this variable from the GAM, with all factors reserved, equals 267.35; Deviance explained = 55.2%; EDF, estimated degrees of freedom; Ref. df, reference degrees of freedom.

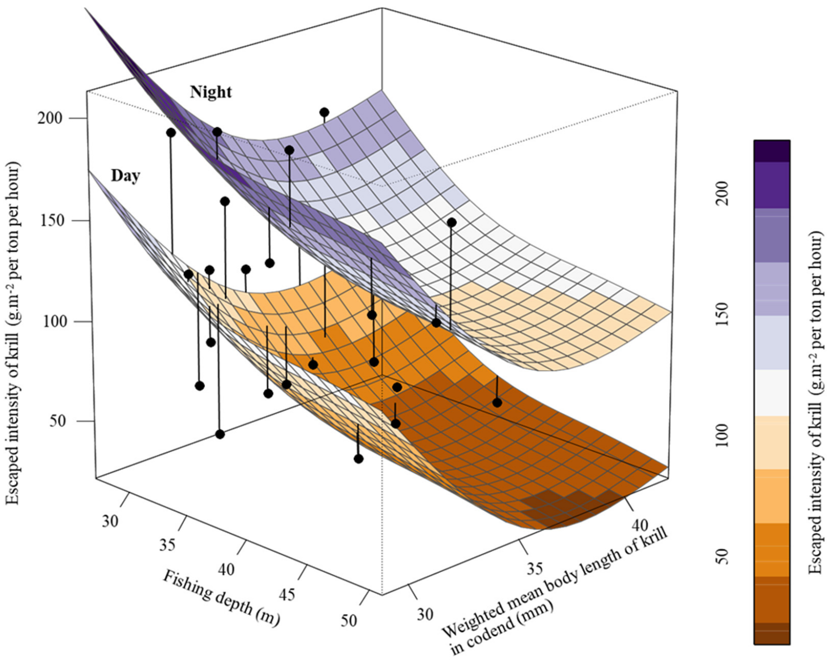

Figure 6. Diurnal (day-night), fishing depth, and weighted mean body length of krill in the codend influenced the escape intensity of krill from the large mesh sections at the front of a commercial trawl (Notes: Black dots represent actual test data).

4. Discussion

4.1. Effect of Liners on Krill Escapement through Mesh

We observed that only a small number of krill managed to evade capture in the second section of the trawl body equipped with a 16 mm liner. Conversely, a substantial quantity of krill was collected in the pocket net located at the rear of the first section, lacking a liner. Thus, we concluded that considerable krill escape through the large mesh in the first section of the trawl body. Therefore, liners should be equipped from the front part of the trawl body to reduce krill catch loss. For the mesh size of the liner, we found that almost no krill escaped through 16 mm mesh size liners entering the pocket net at location 2. Meanwhile, Herrmann et al. [18] found that a krill smaller than 32 mm of body length has a considerable possibility to escape through the 16 mm mesh size liner of the whole trawl body. Furthermore, krill are robust and mostly survive after escaping through the net mesh opening [29]. The escaped small krill become a supplement to the resource population and provide food sources for juveniles of some channichthyids and nototheniids, as well as adults of some myctophids. Thus, considering commercial krill trawls are typically low tapered constructions over 100 m in length [3], the segmented degraded mesh size of the liner will be a better strategy to release juvenile krill before entering the codend. However, the mesh size of the specific configuration of liner needs to be determined in the future research.

4.2. Factors Affecting the Escape Intensity of Krill through Large Mesh Openings

Krill has a relatively small body size, with the maximum body length caught in commercial krill trawls being around 60 mm [19]. Therefore, krill can swim freely through the rope and large-mesh sections. Although krill tend to display a more limited response to stimuli presented by netting, these sections still herd the krill into the small-mesh sections (or sections with liners) and enter the codend [30]. Along the path from the mouth area to its small-mesh part, the krill density increases by about 8-fold to 16-fold compared with its concentration outside the trawl [31]. In this study, we found that fewer escapes occurred during the day hauls in shallow fishing depths compared to at night in deep fishing depths. Moreover, the escape intensity of the krill was length-related.

4.2.1. Effect of Diurnal Patterns and Fishing Depth on Krill Escape

Krill swarms in small areas could be classified according to the diurnal cycle (day-night) and the layer of the swarm. This classification also showed some separation based on krill size and maturity, but such a separation was not obvious [32]. This discovery was confirmed by our finding that there were no significant differences in the body length frequency of krill retained in the codend between the day and night. However, there was a significant diurnal difference in the PSI of body length composition between the pocket net and the codend. The frequency of small krill individuals of less than 30 mm in body length collected in the pocket net was significantly higher during the day. GAM analysis also showed that the diurnal (day-night) pattern significantly influenced the escape intensity of the krill. Moreover, the escape intensity of the krill decreased with increased fishing depth.

These findings suggest that the daily pattern and fishing depth affect the escape intensity of krill due to the visual reaction of krill to the netting panel. Kawaguchi et al. [33] observed that dark objects would be perceived by the krill as a threat, forcing the krill to the far side. Similarly, trawl netting exerts visual pressure on the krill, forcing them to move away from the netting panel. During the day in shallow fishing depths, krill can see the twine of the netting more easily and keep away from the netting. Conversely, krill would fail to perceive the netting due to low light levels that reduce visual clues regarding netting presence [34]. Thus, krill are more likely to contact the netting and enter the pocket net of the haul in deep water at night.

4.2.2. Effect of Body Length on Krill Escape

In this study, we found a positive correlation in the weighted mean body length of krill between the pocket net and the codend. However, the weighted mean body length of the krill in the pocket net was significantly smaller than that in the codend of the same haul. These findings indicate that visual stimulation affecting krill escape was body length-related. Previous studies showed that krill often react with a tail-flip response, darting backward by tail-swimming at high speed away from the stimulus, with the backward velocity positively related to the body lengths of the krill [35]. Larger individual krill have better response capability and swimming speed than smaller ones [10]. Thus, larger krill enable themselves to move away quickly and avoid contacting the netting. Therefore, the frequency of krill over 30 mm in the pocket net at location 1 was less than that in the codend. Along with the general trend, escape intensity of the krill decreased with the increase in size of the codend, although there was a slight increase when weighted mean body length of krill was over 38 mm.

5. Conclusions

This study investigated the escape intensity of krill that passed through the large mesh at the front end of a commercial trawl. The results showed that a substantial fraction of krill escaped in the front large mesh section of the trawl body. In addition, the 16 mm mesh size of liners in the front part effectively reduced catch losses. Therefore, almost no krill over 30 mm escaped through the mesh opening entering the pocket net at location 2. Moreover, the retention probability of the krill in the codend, particularly for larger individuals, was higher during the day than that at night. These findings provide insight into the design of krill trawls, and indicate that liners should be equipped from the front part of the trawl body. Meanwhile, the mesh size and arrangement of liners in krill trawls still need further investigation to determine the quantitative mesh size of the liner in different sections of the trawl.

Author Contributions: Conceptualization, Z.W., H.T. and L.X.; Data curation, Z.W.; Formal analysis, Z.W.; Funding acquisition L.W. and Z.W.; Investigation, Z.W.; Methodology, Z.W., H.T. and L.X.; Writing—review & editing, Z.W., L.W., Y.W., H.T. and L.X. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the Shanghai Sailing Program (23YF1459700), the National Natural Science Foundation of China (32002444), and the Marine S&T Fund of Shandong Province for Qingdao Marine Science and Technology Center (No. 2022QNLM030002-2).

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The data generated during and/or analyzed during the current study are available from the corresponding authors upon reasonable request.

Acknowledgments: We thank China Fisheries Co., Ltd. (Beijing, China). for providing their trawlers and crew to make this onboard experiment possible. We thank Pingguo He and Jian Zhang for their suggestions during revision.

Conflicts of Interest: The authors declare no conflict of interest. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript; or in the decision to publish the results.

References

1. Atkinson, A.; Siegel, V.; Pakhomov, E.A.; Jessopp, M.J.; Loeb, V. A re-appraisal of the total biomass and annual production of Antarctic krill. *Deep Sea Res. Pt. I* **2009**, *56*, 727–740. [CrossRef]
2. CCAMLR. Fisheries/Krill-Fisheries. Available online: https://www.ccamlr.org/en/fisheries/krill-fisheries (accessed on 1 October 2023).
3. Krag, L.A.; Krafft, B.A.; Engås, A.; Herrmann, B. Collecting size-selectivity data for Antarctic krill (*Euphausia superba*) with a trawl independent towing rig. *PLoS ONE* **2018**, *13*, e0202027. [CrossRef] [PubMed]

4. CCAMLR. Gear Diagram of Longteng. Available online: https://www.ccamlr.org/en/system/files/gear_diagrams/100221-net2-gear-diagram-longteng-2018.jpg (accessed on 1 October 2023).
5. CCAMLR. Gear Diagram of Saga-Sea-and-Antarctic-Sea. Available online: https://www.ccamlr.org/en/system/files/gear_diagrams/90407-saga-sea-and-antarctic-sea-net-diagram.pdf (accessed on 1 October 2023).
6. CCAMLR. GEAR Diagram of Antarctic Sea. Available online: https://www.ccamlr.org/en/system/files/gear_diagrams/104905-antarctic-sea-net-diagram.pdf (accessed on 1 October 2023).
7. CCAMLR. Gear Diagram of Sejong. Available online: https://www.ccamlr.org/en/system/files/gear_diagrams/90565-net.docx (accessed on 1 October 2023).
8. CCAMLR. Gear Diagram of Furonghai. Available online: https://www.ccamlr.org/en/system/files/gear_diagrams/100218-net1-gear-diagram-furonghai-2018.jpg (accessed on 1 October 2023).
9. Marr, J.W.S. The natural history and geography of the Antarctic krill (*Euphausia superba Dana*). *Discov. Rep.* **1962**, *32*, 33–464.
10. Johnson, M.; Tarling, G. Influence of individual state on swimming capacity and behaviour of Antarctic krill *Euphausia superba*. *Mar. Ecol. Prog. Ser.* **2008**, *366*, 99–110. [CrossRef]
11. Kanda, K.; Takagi, K.; Seki, Y. Movement of the larger swarms of Antarctic krill *Euphausia superba* off Enderby Land during 1976–1977 season. *J. Tokyo Uni. Fish.* **1982**, *68*, 24–42.
12. Newland, P.L.; Chapman, C.J. The swimming and orientation behaviour of the Norway lobster, *Nephrops norvegicus* (L.), in relation to trawling. *Fish. Res.* **1989**, *8*, 63–80. [CrossRef]
13. Polet, H. Codend and whole trawl selectivity of a shrimp beam trawl used in the North Sea. *Fish. Res.* **2000**, *48*, 167–183. [CrossRef]
14. Říha, M.; Jůza, T.; Prchalová, M.; Mrkvička, T.; Čech, M.; Dratík, V.; Muška, M.; Kratochvíl, M.; Peterka, J.; Tušer, M.; et al. The size selectivity of the main body of a sampling pelagic pair trawl in freshwater reservoirs during the night. *Fish. Res.* **2012**, *127–128*, 56–60. [CrossRef]
15. Krag, L.A.; Herrmann, B.; Iversen, S.A.; Engås, A.; Nordrum, S.; Krafft, B.A. Size Selection of Antarctic Krill (*Euphausia superba*) in Trawls. *PLoS ONE* **2014**, *9*, e102168. [CrossRef]
16. Noack, T.; Madsen, N.; Mieske, B.; Frandsen, R.P.; Wieland, K.; Krag, L.A. Estimating escapement of fish and invertebrates in a Danish anchor seine. *ICES J. Mar. Sci.* **2017**, *74*, 2480–2488. [CrossRef]
17. Czubek, H. Studies on performance capacity and selectivity of trawls used for Antarctic krill fisheries. *Pol. Polar Res.* **1981**, *2*, 131–142. Available online: https://journals.pan.pl/Content/111564/PDF/1981_1-2_131-142.pdf (accessed on 14 December 2023).
18. Herrmann, B.; Krag, L.A.; Krafft, B.A. Size selection of antarctic krill (*euphausia superba*) in a commercial codend and trawl body. *Fish. Res.* **2018**, *207*, 49–54. [CrossRef]
19. Wang, Z.; Tang, H.; Herrmann, B.; Xu, L. Catch Pattern for Antarctic krill (*Euphausia superba*) of Different Commercial Trawls in Similar Times and Overlapping Fishing Grounds. *Front. Mar. Sci.* **2021**, *8*, 670663. [CrossRef]
20. Matsushita, Y.; Inoue, Y.; Shevchenko, A.I.; Norinov, Y.G. Selectivity in the codend and in the main body of the trawl. *ICES J. Mar. Sci.* **1993**, *196*, 170–177.
21. Williams, K.; Punt, A.E.; Wilson, C.D.; Horne, J.K. Length-selective retention of walleye pollock, *Theragra chalcogramma*, by midwater trawls. *ICES J. Mar. Sci.* **2011**, *68*, 119–129. [CrossRef]
22. Williams, K.; Wilson, C.D.; Horne, J.K. Walleye pollock (*Theragra chalcogramma*) behavior in midwater trawls. *Fish. Res.* **2013**, *143*, 109–118. [CrossRef]
23. CCAMLR. Scientific Observer's Manual—Krill Fisheries—Version 2023. CCAMLR: Hobart, Australia; p. 8. Available online: https://www.ccamlr.org/en/system/files/e-SISO%20Manual%20Krill%20Fisheries%202023.pdf (accessed on 1 October 2023).
24. Newman, R.M. Comparison of encounter model predictions with observed size-selectivity by stream trout. *J. N. Am. Benthol. Soc.* **1987**, *6*, 56–64. [CrossRef]
25. Hastie, T.; Tibshirani, R. Generalized additive models. *Stat. Sci.* **1986**, *1*, 297–310. [CrossRef]
26. Jensen, O.P.; Seppelt, R.; Miller, T.J.; Bauer, L.J. Winter distribution of blue crab Callinectes sapidus in Chesapeake Bay: Application and cross-validation of a two-stage generalized additive model. *Mar. Ecol. Prog. Ser.* **2005**, *299*, 239–255. [CrossRef]
27. Tang, H.; Xu, L.; Zhou, C.; Wang, X.; Zhu, G.; Hu, F. The effect of environmental variables, gear design, and operational parameters on sinking performance of tuna purse seine setting on free-swimming schools. *Fish. Res.* **2017**, *196*, 151–159. [CrossRef]
28. O'Connell, M.; Hurley, C.B.; Domijan, K. Conditional visualization for statistical models: An introduction to the condvis package in R. *J. Stat. Softw.* **2016**, *81*, 1–20. [CrossRef]
29. Krafft, B.A.; Krag, L.A.; Engås, A.; Nordrum, S.; Bruheim, I.; Herrmann, B. Quantifying the Escape Mortality of Trawl Caught Antarctic Krill (*Euphausia superba*). *PLoS ONE* **2016**, *11*, e0162311. [CrossRef]
30. Kasatkina, S.M. Selectivity of commercial and research trawls in relation to krill. *CCAMLR Sci.* **1997**, *4*, 161–169. Available online: https://www.ccamlr.org/en/system/files/science_journal_papers/11kasatkina.pdf (accessed on 1 October 2023).
31. Voronina, N.M.; Pakhomov, E.A. How accurate are trawl krill biomass estimates? *Oceanology* **1998**, *38*, 211–212.
32. Ricketts, C.; Watkins, J.L.; Priddle, J.; Morris, D.J.; Buchholz, F. An assessment of the biological and acoustic characteristics of swarms of Antarctic krill. *Deep Sea Res. Pt. I.* **1992**, *39*, 359–371. [CrossRef]
33. Everson, I.; Bone, D.G. Effectiveness of the RMT8 system for sampling krill (*Euphausia superba*) swarms. *Polar Bio.* **1986**, *6*, 83–90. [CrossRef]

34. Kawaguchi, S.; King, R.; Meijers, R.; Osborn, J.E.; Swadling, K.M.; Ritz, D.A.; Nicol, S. An experimental aquarium for observing the schooling behaviour of Antarctic krill (*Euphausia superba*). *Deep Sea Res. Pt. II* **2010**, *57*, 683–692. [CrossRef]
35. Hamner, W.M. Aspects of schooling in *Euphausia superba*. *J. Crustac. Biol.* **1984**, *4*, 67–74. [CrossRef]