Received: 9 January 2023 | Revised: 24 March 2023 | Accepted: 25 March 2023
DOI: 10.1111/fme.12625

Fisheries Management and Ecology
WILEY

ARTICLE

Antarctic krill (*Euphausia superba*) catch weight estimated with a trawl-mounted echosounder during fishing

Bjørn Arne Krafft[1] | **Ludvig A. Krag**[2] | **Ronald Pedersen**[1] | **Egil Ona**[1] | **Gavin Macaulay**[1]

[1]Institute of Marine Research, PO Box 1870, Nordnes, Bergen, NO-5817, Norway
[2]DTU Aqua, Natl Inst Aquat Resources, Hirtshals, DK-9850, Denmark

Correspondence
Bjørn Arne Krafft, Institute of Marine Research, PO Box 1870, Nordnes, Bergen NO-5817, Norway.
Email: bjorn.krafft@imr.no

Funding information
Havforskningsinstituttet; Royal Norwegian Ministry of Fisheries and Coastal Affairs

Abstract

Reporting reliable catch weight estimates is important for all fisheries management. This study explores the potential for precise and direct estimation of catch weight (green weight) for the Antarctic krill (*Euphausia superba*) fishery by employing a high frequency acoustic sensor in the trawl. Trials were performed off the coast of the South Orkney Islands during February 2020 using a scientific macroplankton trawl and echosounder providing a 18° beam pointing downwards across the fishing circle at the trawl mouth. The acoustically estimated catch weight and the observed catch weight had a linear relationship ($R^2 = 0.87$, $F(1,10) = 69.6$, $p < 0.000$) where the acoustically estimated catch weight significantly predicted actual catch weight ($\beta = 1.20$, $p = 0.000$). The acoustic vertical densities of krill increased toward the center of the trawl opening suggesting that krill were herded during fishing. The current study demonstrates that acoustically based catch weight monitoring has the potential to be used for reporting total krill catch weight in each trawl, potentially in real-time, and that similar methods could also be employed in similar types of trawl fisheries.

KEYWORDS
echo-integration, echosounder, fisheries management, krill, weight

1 | INTRODUCTION

Antarctic krill (*Euphausia superba*) are harvested using pelagic trawls in an international fishery, primarily in the Scotia Sea and along the Antarctic Peninsula (48.1–48.4 subareas; Nicol et al., 2012). Total biomass of krill in these fishing areas was 62.6 Mt in 2019 (Krafft et al., 2021), which was similar to a synoptic survey in 2000 (60.3 Mt; CCAMLR, 2010). The krill stock is regarded as one of the world's most underexploited (FAO, 2005; Garcia & Rosenberg, 2010) and current annual harvest levels of ~450 kt are less than the precautionary catch limit for this subarea (in 48.1–48.4), which was set at 620 kt by the Commission for the Conservation of Antarctic Marine Living Resources (CCAMLR), who manage these krill fisheries. Due to increasing demand for marine proteins and lipids, the development of new harvesting and processing technologies, and an expansion in the range of products made from krill, demand for krill in the Southern Ocean is expected to increase.

The fishery targets krill swarms using large pelagic conventional midwater otter trawls (60 × 50 m mouth openings) to land catches in one tow of about 10 t (Budzinski et al., 1985). Some trawls are emptied at the surface by a pumping system, but more usually the catch is hauled on deck. Recently developed "eco-harvesting technology" (patent WO2005004593) transports catch continuously during fishing to a production deck through a vacuum hose attached to the codend. This technique is used by midwater beam trawlers that operate two trawls at a time with up to 26 × 26 m trawl mouth openings (www.ccamlr.org).

A variety of methods are used by vessels to estimate catch of krill taken onboard (green weight), including those based on codend volume, holding tank volume, measurements from flow meters, flow scales, and other weight data of krill sampled along the onboard processing line, including krill meal and concentrate product weights (e.g., CCAMLR, 2019a, 2019b; Skaret et al., 2018). Continued development is needed for methods to precisely estimate green weight of catch and associated uncertainties of krill caught across the krill fishing fleet (CCAMLR, 2015; paragraphs 2.13 to 2.16). To determine where the catch originates with high geographical resolution, catch weighing methods should ideally be able to match catch rates with position of individual vessels. Preferably, green weight of krill should be measured directly after landing on deck, although such methods are challenging and time consuming due to large catch sizes and risk of product degradation.

Recent commercial availability of high frequency self-contained echosounders provides an opportunity to estimate biomass from inside the trawl during fishing. Transducers attached to the trawl that project forward or downwards have been used to improve estimates of organism density below the trawl and to detect individuals in front of, entering, or in the vicinity of trawls, to describe behavior of deep-water and mesopelagic fish species (Ryan et al., 2009; Underwood et al., 2020). A transducer with a narrow beam looking across the trawl cross-section could representatively measure biomass density caught by a net, dependent somewhat on homogeneity of krill density distribution inside a trawl. Densities can be integrated over a short period to measure relative dynamics of the catch in time and space, and when total catches become available, to subsequently distribute the recorded total catch weight in time and space.

In this study, a split-beam echosounder was attached behind the fishing circle of the trawl to determine if echosounder data could be used to directly estimate catch quantity for a range of spatial and temporal resolutions. Catch estimates were validated by weighing the whole catch from each haul. The technology may, in its current form or in a further developed version, be used as standard across the diverse Antarctic krill fishing fleet, but could also be applicable to the management of other types of trawl fisheries. It can also be used to improve estimates of krill mean target strength (TS) that are required for the conversion of acoustic backscatter to biomass.

2 | METHODS

The study area was off the coast of the South Orkney Islands (60°35° S, 45°30° W) during February 2020 onboard the Norwegian stern trawler FV *Saga Sea* (operated by Aker Biomarine AS, Oslo, Norway). Trawl tows were performed on acoustic registrations, detected using Simrad EK80 General Purpose Transceivers connected to hull-mounted transducers. The trawl used for experiments was a 42-m-long macroplankton survey trawl, with a 6 × 6 m mouth opening constructed of 7 mm (stretched) diamond-shaped mesh from the fishing circle (stretched circumference of a trawl or seine expressed as the number of meshes round at the center of the front edge of the belly multiplied by the mesh length, Wileman et al., 1996) to the codline (Krafft et al., 2010, 2018). The trawl was equipped with a transducer (ES70-18CD 70 kHz, Simrad Kongsberg Maritime AS) that provided an 18° beam opening angle, mounted at the fishing circle pointing downwards vertically across the 6 × 6 m trawl mouth cross-section (Figure 1). Area of the acoustic beam (A_{beam}), based on geometry of the trawl cross-section and the beam angle, was 16% of the area covered by the trawl opening ($36\,\text{m}^2 = 6\,\text{m} \times 6\,\text{m}$):

$$A_{\text{beam}} = \frac{ab}{2} = a^2 \tan\frac{18}{2}^{\circ} = 5.7\,\text{m}^2.$$

A self-contained scientific echosounder system (SIMRAD Wide-Band Autonomous Transceiver (WBAT); Simrad Kongsberg Maritime AS) was attached to the beam of the trawl (Figure 1). Prior to deployment, the echosounder was calibrated using standard methods (Demer et al., 2015) with a tungsten carbide sphere of diameter 38.1 mm. The sphere was suspended ~12 m below the transducer, which was ~5 m below the surface and moved throughout the beam while recording backscatter data. Data were processed using the calibration utility in the Simrad EK80 software. The WBAT was configured to generate a linear frequency modulated transmit pulse (55–90 kHz) over a 2.048 ms duration at 300 W transmit power every 0.3 s. A narrowband calibration at 70 kHz was obtained, with the broadband pulse split into three narrowband channels (55–65 kHz, 65–75 kHz, 75–90 kHz) with nominal pulse durations of 0.585, 0.585, and 0.878 ms, respectively, and transmit power of 300 W, and analyzed for the 65–75 kHz channel using the 70 kHz narrowband calibration. A narrowband calibration of a 333 kHz transducer (at 256 ms

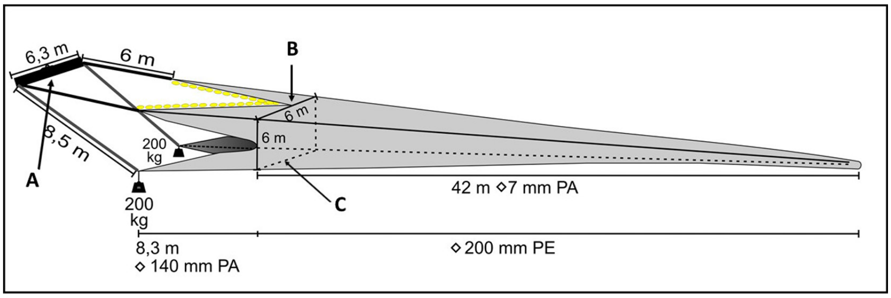

FIGURE 1 The standard trawl, beam, and towing rig used for 20 trawl hauls in waters off the South Orkney Islands during 12–15 February 2020. Location of the echosounder system (A) and associated transducers (B and C) are shown. Yellow ovals illustrate trawl floats.

pulse duration, 50 W transmit power) was conducted immediately after the 70 kHz calibration.

A CTD (Seabird; https://seatronics-group.com) cast carried out next to the transducer provided a sound speed value of 1482 m s^{-1} and acoustic absorption was estimated to be 23.0 dB km^{-1}. Sound speed was calculated following Fofonoff and Millard (1983) and absorption following Francois and Garrison (1982a, 1982b).

A pressure sensor connected to the WBAT started logging data once the unit exceeded a depth of 8 m during deployment of the trawl and stopped logging when the unit passed 4 m of depth during haul-back.

A depth sensor (Simrad FS70, www.kongsberg.com) attached to the center of the trawl headline transferred measurements to the wheelhouse for targeting the trawl onto acoustic registrations of krill. A Seabird CTD attached to the trawl beam logged depth, salinity, and temperature every 10 s. The trawl was obliquely towed with an average trawling speed through water of ~2 knots (1 m s^{-1}).

When the trawl was hauled back onboard, the entire codend catch was emptied into buckets on deck. The trawl was then hung from a crane and flushed with water to wash out biological remains stuck in the netting into a container to be included in the catch for the given haul. The entire catch was weighed using a motion-compensated marine scale (www.marel.com) and a random subsample of 300–400 krill were measured in length (±1 mm) from the anterior margin of the eye to the tip of telson, excluding setae (Marr, 1962).

Echosounder data were viewed as an echogram (Figure 2) in the LSSS postprocessing system (LSSS, v2.11.0; Korneliussen et al., 2016) and data selected from a range of 1.75 m (immediately after the end of the transmit pulse ringdown) to just before echoes from the lower part of the trawl (typically between 4 and 7 m). All pings that were within the period when the trawl was judged to be fishing were selected as data. In some datasets, noise and other interference in the echogram were excluded from data selection, particularly some bubble- and turbulence-related noise at the start or end of hauls. The nautical area scattering coefficient (s_A [m^{2}nmi^{-2}], MacLennan et al., 2002) for that region was calculated by LSSS and exported over the entire trawl opening, and in 0.2-m high layers to describe vertical distribution of krill inside the trawl opening.

Backscattering data from each trawl haul were converted to weight of krill passing through the echosounder beam during each trawl haul. Krill length frequencies from each trawl haul were combined into a single length frequency to derive a conversion factor, C, between backscattering, s_A, and observed krill density:

$$C = \frac{\sum f_i w(l_i)}{\sum f_i \sigma_{sp}(l_i) 1852^2}$$

where f_i is the frequency of occurrence of the i^{th} class of krill length l_i, $w(l_i)$ the mass of a krill of length l_i, $\sigma_{sp}(l_i)$ the spherical scattering cross-section of a krill of length l_i at the echosounder frequency, and an 1852^2 conversion from nmi^2 to m^2. The spherical scattering cross-section was obtained from the target strength of krill:

$$\sigma_{sp} = 4\pi 10^{TS/10}$$

where TS was obtained from an acoustic scattering model of krill at 70 kHz (Calise & Skaret, 2011; Demer & Conti, 2005). Krill length was converted into mass using the CCAMLR relationship (Krafft et al., 2021):

$$w = 2.236 \times 10^6 \times l^{3.314}$$

where w is the mass [g] and l is the length [mm] of an individual krill. Krill density during the trawl haul was then estimated as:

$$\rho = s_A C$$

where ρ is krill areal density [g m^{-2}]. If area density observed by the echosounder was representative of areal density in the entire trawl

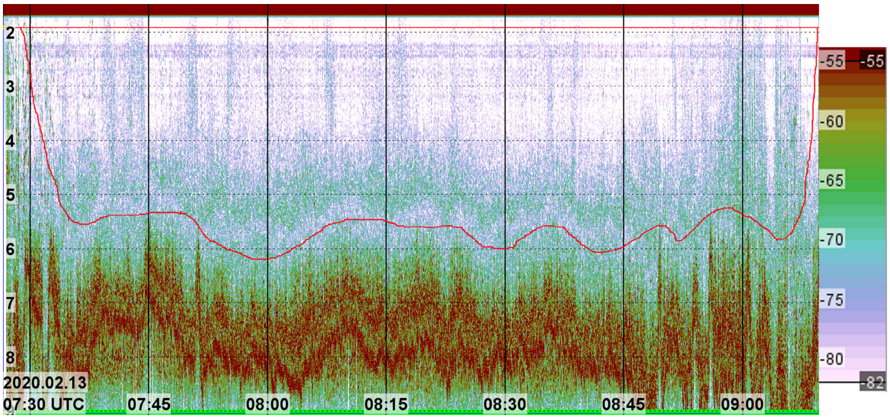

FIGURE 2 Echogram from trawl haul 9 showing the echo from the trawl ground rope (thick red band at 6–8 m range) and the region used to estimate krill density, s_A (enclosed by the red polygon) in waters off the South Orkney Islands on 13 February 2020. Moderate amplitude echoes at 4–6 m range from the trawl through the transducer beam pattern side lobes were excluded from echo-integration. The y-axis is in meters and the x-axis is time of day (hours:minutes, UTC).

opening (in particular, any shadowing effects due to high organism density were not significant over short ranges involved), krill biomass that entered the trawl was then:

$$b = \frac{\rho d w_{trawl}}{1000}$$

where b is the total krill biomass [kg], d the distance travelled by the trawl while fishing [m], and w_{trawl} width of the trawl opening [m]. A linear regression was used to test if acoustically estimated catch weight was significantly related to actual catch weight.

Six additional trawl tows were configured with an upward-looking narrowband 70 kHz acoustic beam (512 ms pulse duration, 300 W transmit power, 18° opening angle) and a narrowband 333 kHz downward-looking beam (256 ms pulse duration, 50 W transmit power, 7° opening angle), driven by the same WBAT echosounder. The echosounder was configured to generate repeated 100 pings at 70 kHz, followed by 100 pings at 333 kHz, with a ping interval of about 0.33 s. Data were processed the same as for single channel data to obtain the vertical distribution of backscattering from upward- and downward-looking transducers. The mean distance between the transducers was estimated from the echo range of the trawl headline (for the upward-looking transducer) and the trawl bottom (for the downward-looking transducer). To maintain consistency for acoustic catch weight analysis, echosounder data from the 70/333 kHz configuration was not used to acoustically estimate trawl catch.

Echoes from individual krill were present in echosounder data and estimates of in-situ target strength were extracted using a single target detection algorithm in LSSS (Korneliussen et al., 2016). The single echo detector (SED) used a minimum TS of −100 dB, a pulse length determination level of 6 dB, echo duration limits of 0.01 and 1.8 (relative to the nominal pulse duration), a maximum beam gain compensation of 6 dB, and a maximum allowable phase deviation of 8 steps. Target strength distributions were compared by applying the CCAMLR modelled krill target strength at 70 kHz (Calise & Skaret, 2011; Demer & Conti, 2005) to the trawl krill length distribution.

3 | RESULTS

Of 20 trawl hauls, 14 were with the downward-looking 70 kHz configuration and six were with the dual 70/333 kHz configuration. Fifteen of 20 trawl hauls were during the day (Table 1). Towing time ranged 23–167 min and maximum towing depth ranged 36–199 m (towing depth of seven trawls was not measured due to equipment failure or procedural errors). Krill averaged 38.7 mm and 95% were 30–50 mm in length over all trawls (Figure 3).

Acoustic catch weight explained 79% of the variation in actual catch weight, but acoustic catch weight was consistently lower than actual catch weight. Actual catch weight could be estimated (bias corrected) from daytime acoustic catch weight as actual catch weight = 1.45 * acoustic catch weight − 14.7 ($R^2 = 0.79$, $F_{1,9} = 37.8$, $p < 0.001$; Table 2, Figure 4). The regression slope was not significantly different from unity (95% confidence interval 0.91–1.98).

TABLE 1 Start time, duration, and maximum depth for 20 trawl hauls in waters off the South Orkney Islands during 12–15 February 2020.

Haul no.	Start time (UTC)	Towing duration (min)	Max towing depth (m)
1	13:29	31	84
2	18:49	29	199
3	19:45	31	145
4	20:44	28	167
5[a]	23:43	14	41
6[a]	01:02	23	n/a
7	04:33	31	39
8	05:36	42	36
9	08:30	99	110
10	11:51	100	160
11	15:10	81	152
12	21:36	73	130
13[a]	23:18	70	52
14	07:32	51	78
15[a]	02:01	39	n/a
16[a]	03:06	56	n/a
17	04:16	56	n/a
18	05:42	64	n/a
19	07:39	80	n/a
20	09:40	167	n/a

[a] Indicates that the trawl tow was at night (between civil twilight times). Towing depth was not available for all trawl hauls (n/a). Hauls 15–20 used the 70/333 kHz echosounder configuration.

Vertical distribution of krill density in the trawl opening was non-uniform (Figure 5), with a peak generally between 2.5 and 5 m from the transducer, and concentrated in the center of the trawl body. Trawl hauls with an upward- and downward-looking transducer pair had similar vertical densities (Figure 6).

In-situ target strength TS (re 1 m^2) averaged −78.0 dB (Figure 7) and ranged broadly from −65 dB to the minimum accepted TS of −100 dB. Single targets were not tracked, so some detected targets were likely not krill. The TS estimated from krill length averaged 2.6 dB higher (−75.4 dB) and was narrower (−70 to −85 dB) than the in-situ estimate (Figure 7).

4 | DISCUSSION

Our findings demonstrated that acoustic-estimated catch weight could be used to estimate actual catch weight inside a scientific Macroplankton trawl, despite the transducer beam only covering

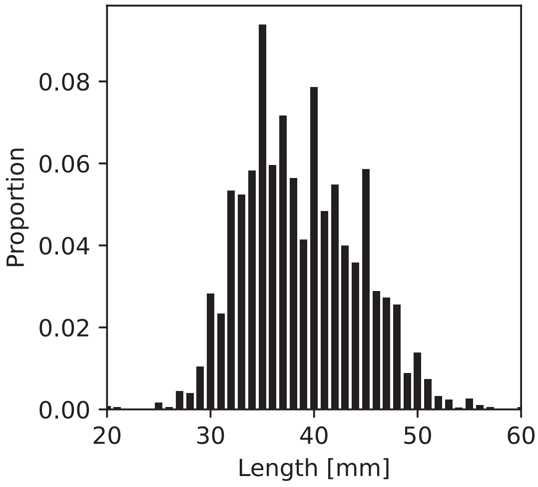

FIGURE 3 Krill length frequency distribution from 20 trawl hauls in waters off the South Orkney Islands during 12–15 February 2020.

TABLE 2 Measured and acoustic-estimated weight of krill caught in 14 individual trawl hauls in waters off the South Orkney Islands during 12–15 February 2020.

Haul no.	Catch weight measured (kg)	Krill length l (cm) mean ± SD	Catch weight acoustic (kg)
1	3.9	39 ± 5	10.8
2	16.4	36 ± 5	32.4
3	30.0	36 ± 4	15.4
4	9.1	41 ± 6	7.5
5[a]	100.3	39 ± 5	89.7
6[a]	133.8	38 ± 4	53.9
7	49.6	42 ± 6	60.3
8	162.5	39 ± 6	104.8
9	11.3	36 ± 4	43.7
10	11.8	36 ± 5	23.4
11	17.6	41 ± 6	25.8
12	81.8	38 ± 5	67.7
13[a]	175.0	38 ± 6	102.6
14	53.7	37 ± 5	29.5

Note: Measured catch weight was obtained by weighing the catch and acoustic-estimated weight was derived from the acoustic backscatter passing underneath the trawl-mounted echosounder.

[a] Indicates the trawl haul was at night (between civil twilight times).

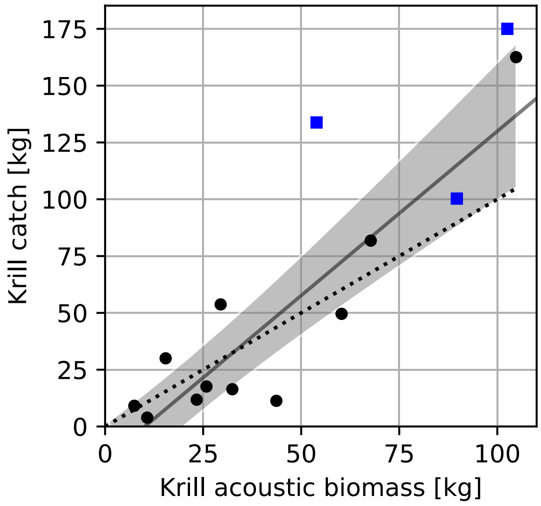

FIGURE 4 Measured trawl catch weight in relation to acoustic-estimated trawl catch weight for 14 trawl hauls with a downward-looking 70 kHz echosounder in waters off the South Orkney Islands during 12–14 February 2020. Day trawls are circles and night trawls are squares. The solid line is a linear least-squares fit to daytime trawl hauls (krill catch = 1.45 * krill acoustic biomass–14.7), the shaded region indicates the 95% confidence interval of the fitted line, and the dotted line is a 1:1 relationship.

16% of cross-sectional trawl area. To obtain reliable acoustic estimates of organisms entering a trawl, where only a small part of the trawl cross-section is monitored, required that the observed catch was representative of the entire trawl cross-section in the observation area. The method we used will be sensitive to the spatial distribution of krill entering a trawl. Further, to monitor and quantify catch levels for management purposes, across a diverse fishing fleet, using different trawl designs, requires a precise and robust methodology to reliably estimate catch weight for each trawl haul. The system we used demonstrates potential to acoustically monitor catch in the Antarctic krill trawl fishery, but further development of the design to cover more of the cross-section of krill trawls (e.g., by using multibeam systems or multiple transducers) and thereby the catch, should provide more reliable and accurate estimates of the catch and be less dependent on variation in distribution of the catch entering the trawl mouth.

We found that krill were concentrated in the vertical center of trawls, which suggested that krill actively avoided trawls, by herding, which is also observed for other fish species in bottom trawls and large-meshed pelagic trawls (Winger et al., 2010). Furthermore, the vertical distribution of krill density was similar in trawls with upward- and a downward-looking transducers, which confirmed that significant quantities of krill were not lost in the dead zone or shadow zone associated with a relatively wide acoustic beam hitting the bottom panel of the trawl. For example, the ability to actively swim inside fishing gears, by herding within trawl netting, is largely affected by towing speed and the animal's swimming ability (He, 1993). However, such catch distributions in a trawl mouth may vary diurnally, among fishing areas, among fishing seasons, or with krill size and density (Glass & Wardle, 1989; Kane et al., 2018).

At night, krill tend to ascend where large quantities can be found close to the surface (Zhou & Dorland, 2004). Given the on/off configuration of the echosounder, significant quantities of krill may have been caught but not registered when the echosounder was shallower than 8 m during night trawl tows. Such bias could explain why acoustic catch weights were significantly less than actual catch weights in two of three night tows, so we did not include night trawl

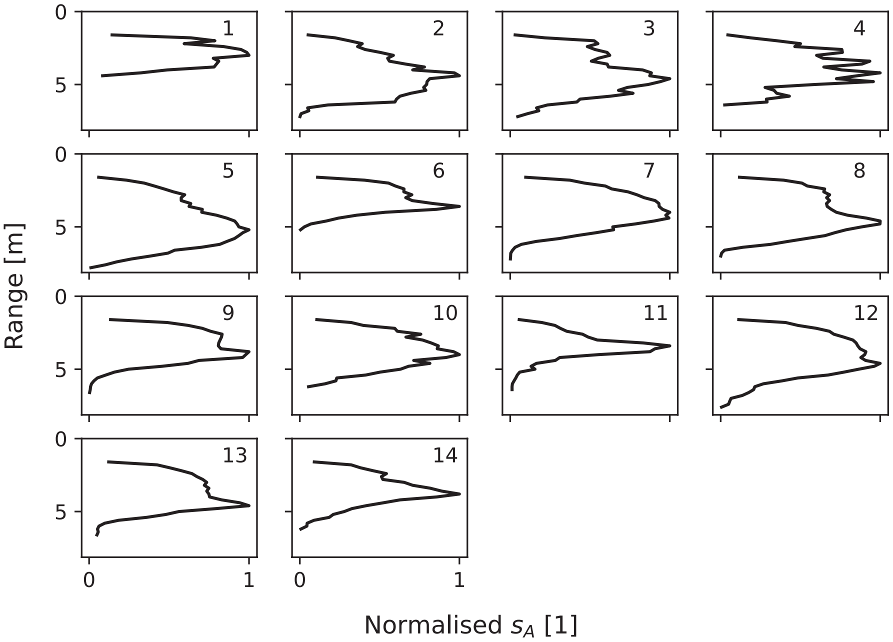

FIGURE 5 Vertical distribution of normalized krill backscattering s_A for 14 trawl hauls in waters off the South Orkney Islands during 12–14 February 2020. Range is the distance from the echosounder transducer and s_A was obtained from 0.2-m thick echo-integration layers.

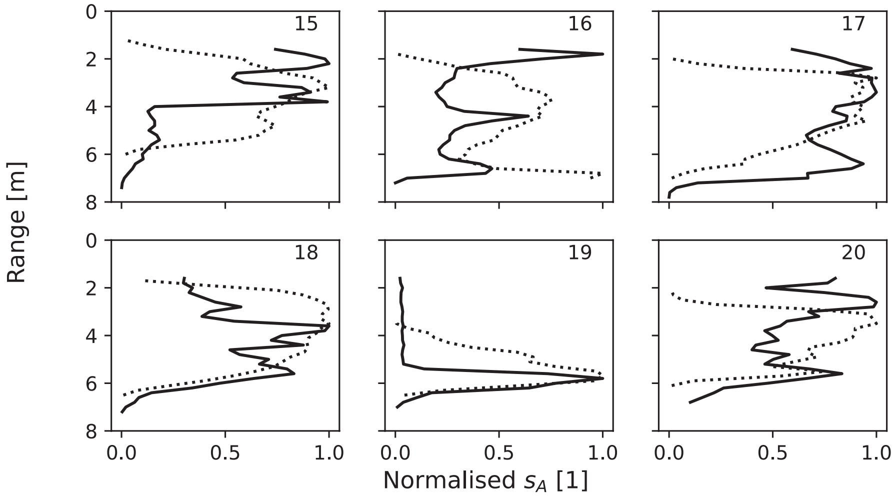

FIGURE 6 Vertical distribution of normalized krill backscattering s_A for 6 trawls with a downward-looking transducer on the trawl beam (solid line) and an upward-looking transducer on the trawl bottom (dotted line) in waters off the South Orkney Islands during 15 February 2020. The trawl tow number is given in each panel.

data in the regression that related acoustic-estimated and actual krill catch weight.

Manual scrutiny of echograms to exclude echoes from the trawl can introduce bias through unintended integration of echo energy from the trawl and other sources of unwanted energy. However, the low noise environment and very strong trawl echoes limited the possibility of this happening because if strong trawl echoes were included, the acoustic catch weight estimates became unreasonably large. For this reason, we anticipate any bias from manual scrutinization to be low. In a commercial setting, this situation may be different, and if so, must be considered. Any automated real-time processing of echosounder data would also need to adequately detect and remove unwanted echo energy.

Conventional trawls are designed with larger meshes in the front that gradually decrease in size toward the codend, while trawls used for continuous pumping are designed with smaller mesh sizes throughout the length of the trawl. Since there is size selectivity for krill in commercial trawls (Herrmann et al., 2018; Krag et al., 2014), the transducer should be positioned in a net section with small meshes to minimize bias of catch weight estimation due to gear size selectivity. Our acoustic system stored data on a submerged echosounder, and data were downloaded after each haul. In a commercial application of such a system, real-time transfer of acoustic data to the vessel by a communication cable would be better, or lower volume processed data could be transmitted acoustically to the vessel.

Antarctic krill are generally regarded as planktonic organisms that drift with currents, but also swim horizontally and vertically in the water column for limited periods of time (Kanda et al., 1982; Kawaguchi & Nicol, 2007; Marr, 1962; Taki et al., 2005). The mechanism that results in size selectivity of krill is not well known (Kasatkina, 1997), but krill may either move passively through a gear during the catching process to randomly escape or actively escape (Krag et al., 2014). Our findings suggest that krill actively avoided trawl netting, because density was higher in the center of the trawl mouth, which indicates that size selectivity of Antarctic krill was more active process than passive.

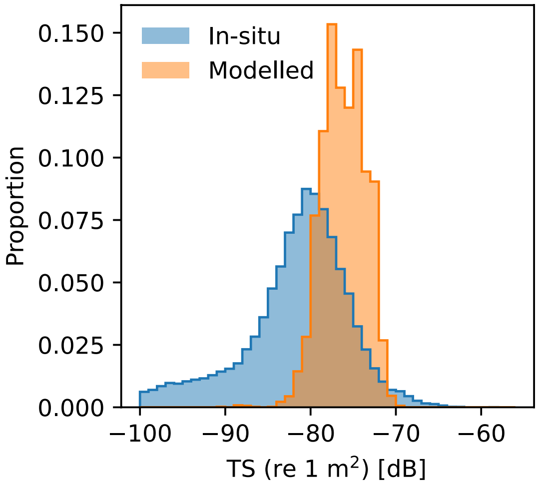

FIGURE 7 Krill target strength (TS) distribution from a trawl-mounted echosounder (blue, in-situ) and a combination of measured trawl krill length and modelled krill TS (orange, modelled) for 20 trawl hauls in waters off the South Orkney Islands during 12–15 February 2020.

Netting in the lower trawl panel gives a strong acoustic backscatter, particularly in krill trawls where multiple layers of netting are used, which precludes acoustic detection of krill within half the pulse length (0.38 m for the 70 kHz transducer, about 6% of the opening height) of the lower trawl panel. This blind zone can potentially be reduced by using an alternative material or netting design that reflects less sound, or by attaching the transducer closer to the trawl opening (e.g., the headline), where it can point down without the beam hitting the bottom of the trawl. Data analysis would then use acoustic data out to the range of the expected trawl opening height. Echograms from hauls in our study also indicate that the transducer attitude was oscillating, which caused a varying blind zone close to the lower trawl netting. A more stable mounting arrangement would reduce transducer movement and thereby improve backscatter biomass estimation. A larger commercial trawl would likely have sufficient drag in the netting to prevent or reduce such transducer movement.

In addition to strong echoes from the trawl at a range of 7–8 m, weaker echoes were also visible at a range of 4–6 m, which were consistent among most trawls and moved in sync with strong trawl echoes. We interpreted such echoes as reflections or reverberations from the trawl that probably occurred through transducer sidelobes, because they were not observed on echograms from the 333 kHz transducer or the upward-looking 70 kHz transducer. Therefore, we conclude that backscatter was likely caused by a combination of mounting position and wider 18° opening angle of the 70 kHz transducer than the 7° opening angle of the 333 kHz transducer.

Weak trawl-related echoes do not significantly affect echo-integration in fish studies, but krill backscatter is of similar strength as these weak echoes, so they can have a larger effect on echo-integration estimates. For this reason, these weak echoes were excluded and for most trawls this led to the maximum echo-integration range being reduced to about 4 m for most of the trawl period. Future work should attempt to minimize weak echoes that can significantly reduce acoustic sampling volume and complicate processing of acoustic data.

Conversion of krill acoustic backscatter into estimated catch weight used krill target strength estimates from an acoustic model of krill. The degree of agreement with actual catch weight confirmed that modelled krill target strength was appropriate and did not induce large error or bias (it also supports the method of deriving absolute biomass from conventional trawl-acoustic surveys of krill, e.g., Krafft et al., 2021). However, the fitted regression slope differed significantly from 1.0, which could have been caused by modelled TS differing from actual TS. Similarly, the TS from in-situ measurements averaged 2.6 dB higher. Systematic registration of bycatch was not made from tows, so the occurrence of other species was likely low. However, in-situ TS may not have represented actual krill TS in trawls. In-situ TS data may have included echoes from other organisms (filtering of krill-like echoes was impossible from the single frequency echosounder used in the experiments). For example, TS echoes of up to −56 dB were observed, which are unrealistic for krill at 70 kHz. Very small Antarctic krill (~10 mm) have a modelled TS of about −100 dB, but life stages of this size are not common in these waters at this time of year (Krafft et al., 2018). The single target detection algorithm may also have misidentified background noise as coming from organisms.

For the development of a new krill management system (CCAMLR, 2017), fishing vessels should collect acoustic data that is suitable for biomass estimation. We demonstrated that in-situ TS estimates, which are essential for biomass calculations, can be obtained from a trawl-mounted echosounder. Use of TS estimates that are contemporaneous with acoustic biomass surveys would likely lead to more accurate biomass estimates. The tilt angle distribution and associated TS estimates of naturally behaving animals is unknown, but we found that in-situ TS estimates were within the range expected from the CCAMLR krill TS model, which itself uses several behavioral and physical krill parameter estimates, such as the tilt angle distribution of organisms.

The high frequency, wideband echosounder system we tested can collect detailed information on single individuals and swarms of krill within and around the trawl. Mounting the system on a trawl reduces range to targets, and the increased range resolution available with a wideband pulse enables high quality in-situ target strength measurements at several frequencies. Krill avoidance in front of trawls can also be monitored (Underwood et al., 2020) and for understanding individual behavior inside the trawl. Tracking groups or individual organisms could provide a detailed picture of krill movement during the catching process, inside and outside trawls (Handegard, 2007; Handegard et al., 2005, 2012).

Uptake of our acoustic method to estimate catch weight will require near real-time catch weight estimates to allow for effective management of catch rates and abnormal events that may occur in the trawl. With techniques such as machine learning and deep learning being used for processing acoustic data, acoustic-based catch estimates may soon become available in near real-time without manual intervention. A near real-time echogram display could also provide information to monitor and mitigate interactions with marine mammals (Krafft, Lindstrøm, et al., 2022). For example, the acoustic signature from a marine mammal differs significantly from individual krill or krill aggregations and could be used to warn trawl operators and allow them to avoid or minimize interactions with the trawl gear.

A trawl-mounted echosounder is a promising tool to estimate krill catch that is easy to implement, and with some improvements, has the potential for commercial use. Improvement in acoustic biomass estimates is achievable by reducing unwanted echoes and increasing coverage of the trawl cross-section. A trawl-mounted echosounder can provide insight into spatial krill behavior inside the trawl for individual organisms, an understudied research area. Such a system could also be used to increase knowledge of herding to improve the effectiveness of harvesting gear and bycatch monitoring (Krafft, Lowther, et al., 2022).

ACKNOWLEDGMENTS

This study is part of the project KRILL, which is supported by the Royal Norwegian Ministry of Fisheries and Coastal Affairs and the Institute of Marine Research in Norway. We would like to extend our gratitude to Aker BioMarine ASA for providing their vessel and crew at no cost and allowing us to collect the material and conduct the experiments. We thank B. Mozfar and A. Rasmussen (IMR), J. Arata (ARK) and A. Luna (Inach) for their assistance during the survey with catch weighing and length measuring of krill. We also thank V. Hadziavdic (Wintershall Dea) for advice on numerical processing. Data in this manuscript are stored at the Norwegian Marine Data Centre, held at the Institute of Marine Research. Access to them is welcomed for collaborative/comparative efforts; contact BAK. We also appreciate the time and effort by the editor Dr Michael Hansen and two anonymous reviewers to improve the manuscript.

CONFLICT OF INTEREST STATEMENT

The authors have no conflicts of interest to declare.

DATA AVAILABILITY STATEMENT

Data available on request from the authors

REFERENCES

Budzinski, E., Bykowski, P. & Dutkiewicz, D. (1985) *Possibilities of processing and marketing of products made from Antarctic krill*. Rome: FAO, p. 46 FAO Fisheries Technical Paper. No. 268.

Calise, L. & Skaret, G. (2011) Sensitivity investigation of the SDWBA Antarctic krill target strength model to fatness, material contrasts and orientation. *CCAMLR Science*, *18*, 97–122.

CCAMLR (Convention on the Conservation of Antarctic Marine Living Resources). (2010) *Report of the 29th meeting of the scientific committee, Hobart, TAS, Australia, 25-29th October, 2010*. SC-CAMLR-XXIX. CCAMLR, Hobart, TAS, Australia.

CCAMLR (Convention on the Conservation of Antarctic Marine Living Resources). (2015) *Report of the working group on ecosystem monitoring and management*. Document WG-EMM-15. CCAMLR, Hobart, TAS, Australia.

CCAMLR (Convention on the Conservation of Antarctic Marine Living Resources). (2017) *Report of the 36th meeting of the scientific committee, Hobart, Australia, 16-20th October, 2017*. SC-CAMLRXXXVI. *CCAMLR*, Hobart, TAS, Australia.

CCAMLR (Convention on the Conservation of Antarctic Marine Living Resources). (2019a) *Comparative analysis of flow meter and codend volume method for estimating green weight in 'Betanzos'23 June 2015*. Document *WG-EMM-15/58*. CCAMLR, Hobart, TAS, Australia.

CCAMLR (Convention on the Conservation of Antarctic Marine Living Resources). (2019b) *Estimation of the green weight of krill caught*. Document *WG-EMM-15/19*. CCAMLR, Hobart, TAS, Australia.

Demer, D.A., Berger, L., Bernasconi, M., Bethke, E., Boswell, K., Chu, D. et al. (2015) *Calibration of acoustic instruments*. pp. 133. ICES Cooperative Research Report No. 326. ISBN 978-87-7482-167-0 ISSN 2707-7144 © 2015 International Council for the Exploration of the Sea https://doi.org/10.17895/ices.pub.5494

Demer, D.A. & Conti, S.G. (2005) New target-strength model indicates more krill in the Southern Ocean. *ICES Journal of Marine Science*, *62*, 25–32.

FAO. (2005) *Review of the state of world marine fishery resources* . Rome: Food and Agriculture Organization of the United Nations (FAO). FAO Fisheries and Aquaculture Technical Paper 457, p. 235.

Fofonoff, P. & Millard, R. (1983) *Algorithms for computation of fundamental properties of seawater*. UNESCO technical Paper in Marine Science, 44 http://hdl.handle.net/11329/109

Francois, R.E. & Garrison, G.R. (1982a) Sound absorption based on ocean measurements. Part I: pure water and magnesium sulphate contributions. *The Journal of the Acoustical Society of America*, *72*, 896–907.

Francois, R.E. & Garrison, G.R. (1982b) Sound absorption based on ocean measurements. Part II: boric acid contribution and equation for total absorption. *The Journal of the Acoustical Society of America*, *72*, 1879–1890.

Garcia, S.M. & Rosenberg, A.A. (2010) Food security and marine capture fisheries: characteristics, trends, drivers and future perspectives. *Philosophical Transactions of the Royal Society B Biological Sciences*, *365*, 2869–2880.

Glass, C.W. & Wardle, C.S. (1989) Comparison of the reactions of fish to a trawl gear, at high and low light intensities. *Fisheries Research*, *7*, 249–266.

Handegard, N.O. (2007) Observing individual fish behavior in fish aggregations: tracking in dense fish aggregations using a split-beam echosounder. *The Journal of the Acoustical Society of America*, *122*, 177–187. Available from: https://doi.org/10.1121/1.2739421

Handegard, N.O., Boswell, K.M., Ioannou, C.C., Leblanc, S.P., Tjostheim, D.B. & Couzin, I.D. (2012) The dynamics of coordinated group hunting and collective information transfer among schooling prey. *Current Biology*, *22*(13), 1213–1217. Available from: https://doi.org/10.1016/j.cub.2012.04.050

Handegard, N.O., Ruben Patel, R. & Hjellvik, V. (2005) Tracking individual fish from a moving platform using a split-beam transducer. *The Journal of the Acoustical Society of America*, *118*, 2210–2223. Available from: https://doi.org/10.1121/1.2011410

He, P. (1993) Swimming speeds of marine fish in relation to fishing gears. *ICES Marine Science Symposium*, *196*, 183–189.

Herrmann, B., Krag, L.A. & Krafft, B.A. (2018) Size selection of Antarctic krill (*Euphausia superba*) in a commercial codend and trawl body. *Fisheries Research*, *207*, 49–54. Available from: https://doi.org/10.1016/j.fishres.2018.05.028

Kanda, K., Takagi, K. & Seki, Y. (1982) Movement of larger swarms of Antarctic krill *Euphausia superba* off Enderby Land during 1976–1977 season. *Journal of the Tokyo University of Fisheries (Japan)*, *68*, 24–42 ISSN: 0040-9014.

Kane, M.K., Yopak, R., Roman, C. & Menden-Deuer, S. (2018) Krill motion in the Southern Ocean: quantifying in situ krill movement behaviors and distributions during the late austral autumn and spring. *Limnology and Oceanography*, *63*, 2839–2857.

Kasatkina, S.M. (1997) Selectivity of commercial and research trawls in relation to krill. *CCAMLR Science*, *4*, 161–169.

Kawaguchi, S. & Nicol, S. (2007) Learning about Antarctic krill from the fishery. *Antarctic Science*, *19*, 219–230.

Korneliussen, R.J., Heggelund, Y., Macaulay, G.J., Patel, D., Johnsen, E. & Eliassen, I.K. (2016) Acoustic identification of marine species using a feature library. *Methods in Oceanography*, *17*, 187–205.

Krafft, B.A., Krag, L.A., Knutsen, T., Skaret, G., Jensen, K.H.M., Krakstad, J.O. et al. (2018) Summer distribution and demography of Antarctic krill (*Euphausia superba*) (Dana, 1852) (Euphausiacea) at the South Orkney Islands, 2011–2015. *Journal of Crustacean Biology*, *38*, 1–7. Available from: https://doi.org/10.1093/jcbiol/ruy061

Krafft, B.A., Lindstrøm, U., Biuw, M. & Lowther, A. (2022) *Develop methods for the co-existence of large baleen whales with a sustainable krill fishery*, *10*. CCAMLR WG-IMAF-2022/01, 10 pp.

Krafft, B.A., Lowther, A. & Krag, L.A. (2022) Bycatch in the Antarctic krill (*Euphausia superba*) trawl fishery. *Fisheries Management and Ecology*, *30*, 154–160.

Krafft, B.A., Macaulay, G.J., Skaret, G., Knutsen, T., Bergstad, O.A., Lowther, A. et al. (2021) Standing stock of Antarctic krill (*Euphausia superba* Dana 1850 (Euphausiacea)) in the Southwest Atlantic sector of the Southern Ocean, 2019. *Journal of Crustacean Biology*, *41*, 1–17. Available from: https://doi.org/10.1093/jcbiol/ruab046

Krafft, B.A., Melle, W., Knutsen, T., Bagøien, E., Broms, C., Ellertsen, B. et al. (2010) Distribution and demography of Antarctic krill in the Southeast Atlantic sector of the Southern Ocean during the austral summer 2008. *Polar Biology*, *33*, 957–968.

Krag, L.A., Herrmann, B., Iversen, S.A., Engås, A., Nordrum, S. & Krafft, B.A. (2014) Size selection of Antarctic krill (*Euphausia superba*) in trawls. *PLoS One*, *9*(8), e102168. Available from: https://doi.org/10.1371/journal.pone.0102168

MacLennan, D.N., Fernandes, P. & Dalen, J. (2002) A consistent approach to definitions and symbols in fisheries acoustics. *ICES Journal of Marine Science*, *59*, 365–369.

Marr, J. (1962) *The natural history and geography of the Antarctic krill (Euphausia superba Dana)* Vol. 32. Discovery Reports. Cambridge: National Institute of Oceanography, Cambridge University Press.

Nicol, S., Foster, J. & Kawaguchi, S. (2012) The fishery for Antarctic krill–recent developments. *Fish and Fisheries*, *13*, 30–40.

Ryan, T.E., Kloser, R.J. & Macaulay, G.J. (2009) Measurement and visual verification of fish target strength using an acoustic-optical system attached to a trawlnet. *ICES Journal of Marine Science*, *66*, 1238–1244. Available from: https://doi.org/10.1093/icesjms/fsp122

Skaret, G., Knutsen, T., Grebstad, F. & Bergstad, O.A. (2018) *Uncertainty in reported geographical distribution and weight of krill catches from Norwegian krill fishing vessels operating continuous fishing systems*. CCAMLR WG-EMM-18/22, 23 pp.

Taki, K., Hayashi, T. & Naganobu, M. (2005) Characteristics of seasonal variation in diurnal vertical migration and aggregation of Antarctic krill (*Euphausia superba*) in the Scotia Sea, using Japanese fishery data. *CCAMLR Science*, *12*, 163–172.

Underwood, M.J., Garcia-Seoane, E., Klevjer, T.A., Macaulay, G.J. & Melle, W. (2020) An acoustic method to observe the distribution and behaviour of mesopelagic organisms in front of a trawl. *Deep Sea Research Part II Topical Studies in Oceanography*, *180*, 104873. Available from: https://doi.org/10.1016/j.dsr2.2020.104873

Wileman, D.A., Ferro, R.S.T., Fonteyne, R. & Millar, R.B. (1996) *Manual of methods of measuring the selectivity of towed fishing gears*. Copenhagen, Denmark: ICES (International Council for the Exploration of the Sea). ICES Cooperative Research Report. Vol. 215, p. 132. Available from: https://doi.org/10.17895/ices.pub.4628

Winger, P.D., Eayrs, S. & Glass, C.W. (2010) Fish behaviour near bottom trawls. In: He, P. (Ed.) *Behaviour of marine fishes: capture processes and conservation challenges*. Hoboken, NJ: Wiley–Blackwell, pp. 67–103 IA, 375. Available from: https://doi.org/10.1002/9780813810966

Zhou, M. & Dorland, R.D. (2004) Aggregation and vertical migration behavior of *Euphausia superba*. *Deep Sea Research Part II Topical Studies in Oceanography*, *51*, 2119–2137.

How to cite this article: Krafft, B. A., Krag, L. A., Pedersen, R., Ona, E. & Macaulay, G. (2023). Antarctic krill (*Euphausia superba*) catch weight estimated with a trawl-mounted echosounder during fishing. *Fisheries Management and Ecology*, *30*, 323–331. https://doi.org/10.1111/fme.12625