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Gear-Specific Impacts of Bottom Trawling on *Arctica islandica* in the Western Baltic Sea

Abstract

The ocean quahog (*Arctica islandica*) is a key species in the Western Baltic Sea with respect to its role in the ecosystem. This species is, however, also classified as endangered. Its vulnerability and various pressures including mobile bottom fisheries are a continous danger to this species. Similar to commercial fisheries in soft bottom areas, individuals of *A. islandica* are frequently caught as bycatch and discarded in scientific bottom otter trawl surveys. In order to quantify gear-specific effects and damage to *A. islandica* bycatch, we performed three trawls within a field experiment off Kühlungsborn (Mecklenburg Bight, Germany) using a standard otter trawl in fisheries research (TV3-520). In total 322 individuals (12.5 kg fresh mass) were caught. In one of the hauls checked in detail (n = 219), 11 % of the shells were broken, mostly close to the umbo. In addition, we used information obtained from 33 hauls with a 3 m beam trawl, 18 hauls with a 2 m beam trawl, and 3 hauls with a 1 m dredge. We observed the highest proportion of broken shells in 3 m beam trawls. Our results illustrate that the effect on the population depends on the type of trawl, net content, local density and size structure of *A. islandica. Our investigation suggests that shell damage* occures in ~ 4 % of the bycaught *A. islandica*. Individuals with broken shells are bound to die, and likely end up as food to fish, snails and echinoderms and have to be considered part of the mortality in the local population of *A. islandica*. Additionally, we observed as much shell debris (by mass) as living bivalves in the bycatch of the otter trawl (12.5 kg shells in 3 hauls, equivalent to ~1255 individuals). This points to substantial accumulation of shells from dead animals and illustrates temporally limited C-storage.

Keywords: Trawling pressure; Shell damage; Infauna bivalves; Mecklenburg Bight

1 Introduction

The ocean quahog (*Arctica islandica*) is considered a key species in the Western Baltic Sea, due to its substantial contribution to the benthic biomass (SCHULZ et al. 2025) and its role in ecosystem functioning as an important food source for e.g. benthic fish, starfish, and predatory snails (ARNTZ & WEBER, 1970), active filter-feeder and efficient bioturbator, relevant for benthic-pelagic coupling and organic material turnover. At the same time, the species is classified as endangered in the Western Baltic (Red List category 3, RACHOR et al. 2013).

Due to its extreme biomass dominance and longevity, the ocean quahog plays a particularly important role in deeper areas of Kiel Bight, Fehmarnbelt (FB) and Mecklenburg Bight (MB) (MARX et al. 2024). Descriptions of the *Arctica* population in the MB date back to 1999 and were published by ZETTLER et al. (2001). A recent comprehensive assessment of the population in its distribution range in the German Baltic Sea indicates that the *A. islandica* population appears relatively stable compared to earlier investigations (SCHULZ et al. 2025). An assessment of monitoring data (Landesamt für Umwelt, Naturschutz und Geologie M.-V., Leibniz Institute for Baltic Sea Research Warnemünde) in the southern and central MB between 2000 and 2018 revealed average abundances with 61 ± 22 ind/m² of *A. islandica* at water depths of 20 – 24 m (5 key stations: 012, 018, KMC20, KMB22, KMA20, 9 – 30 sampling dates each, Fig. 1). Mass recruitment is typically irregular and patchy in the MB, particularly at depth below 15 m. The last mass recruitment event for this key species in this area was documented in 2012/2013 in parts of the MB, and no new successful settlements have been recorded since. A comparison of the average biomasses determined between 2000 and 2018 for the southern MB at the same 5 key stations (13.6 ± 5.8 g ash-free dry mass (AFDM)/m²) further confirms the stabitity of the *A. islandica* population in MB.

Arctica individuals are commonly part of the bycatch in scientific bottom otter trawling, some of them with damaged shells. Commercial fisheries use similar trawling equipment. Beam trawls which we also used in this study however, are not used by commercial fisheries in the Baltic but show clearyly how different gears impact the species. Depending on the size and weight of the gear, bottom trawling in the Baltic Sea can have biogeochemical effects (BRADSHAW et al. 2021; MORYS et al. 2021; FORSTER et al. 2024) especially when otter boards plough deep through sediments. This trawling type is also able to redistribute shells and bivalves at the seafloor, as observed by ARNTZ & WEBER (1970). RUMOHR & KROST (1991) reported damage of 10.6 % of indivdiduals of *Arctica* caught by a specialized dredge equipped with otter boards in the Kiel Bight.

In the context of the detrimental effects that bottom trawling can have on benthic organisms (KRÖNCKE et al., 2011; MAZOR et al., 2021; MCLAVERTY et al., 2023; BRADSHAW et al., 2024), we investigate what kind of impact bottom trawling can have on *A. islandica* and discuss the effects of different gears and its discard. For this aim, evidence on shell damage in *A. islandica* was gathered through an exploratory, non-systematic assessment of the bycatch from different types of fishing gear in the southwestern German Baltic Sea. We compared our findings with underwater video images and additional sparse data on empty shells in order to understand the mechanism and magnitude of a possible impact that bottom trawling and discarding bycatch may have on *Arctica islandica*.

2 Material and Methods

We investigated bottom otter trawls as part of an *in-situ* experiment in an area north of Kühlungsborn near the city of Rostock as well as beam trawls and dredge hauls in FB (both areas in 23 to 24 m water depth) (Fig. 1, Table 1). Sediments at the experimental site and in FB were similar. In the FB, sediments showed an organic content of 6.0 ± 1.3 % (mean ± SD) measured as loss on ignition. Median grain size was determined as 54 ± 9 µm (GOGINA & SCHÖNKE 2020). In the investigation area off Kühlungsborn in the southern MB, organic content was 8.4 ± 1.9 % and median grain size was 38 ± 14 µm.

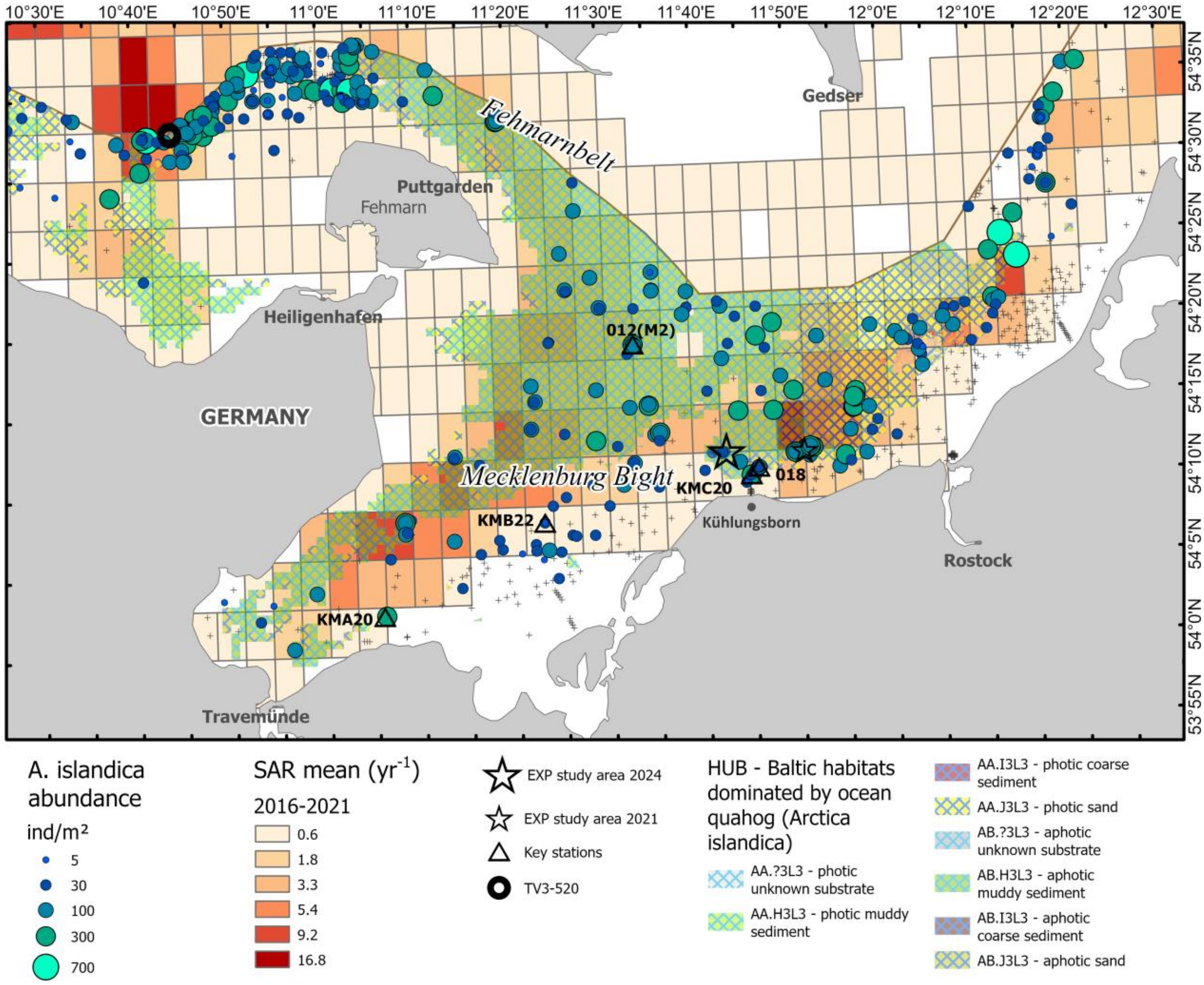

Fig. 1 Distribution (occurrence and abundance) of *A. islandica* in the Mecklenburg Bight (based on data from 2015-2024 from the Leibniz Institute for Baltic Sea Research Warnemünde within the German waters) mapped over the fishing intensity data from ICES (2022) expressed as swept area ratio (SAR) in each 0.05° × 0.05°-degree c-square; red = high mobile bottom-contact fishing intensity. Colored dots represent abundance classes of the ocean quahog. Grey crosses mark stations where the species was absent. Triangles indicate 5 key stations with *Arctica* data from 2000-2018. Black circle marks the otter trawl area in the northern FB.

2.1 Field experiemnt

In July 2024 three hauls with a scientific bottom otter trawl (TV3-520) were conducted off Kühlungsborn from the RV *Clupea* as part of an *in-situ* trawling field experiment within the project “MGF-Ostsee II” (Fig.1). Trawling was performed longitudinally at a towing speed of 3 knots and duration between 12 and 15 minutes with a 20 mm mesh size in the cod end (for detailed trawl specifications see ICES 2017). The otter boards had a surface area of 1.8 m² and a total weight of 205 kg each. Catch composition was quantitatively analyzed onboard. In addition to the fish compostion, the *A. islandica* bycatch was also studied in detail. In total, data of three otter trawl hauls with living ocean quahogs and empty *Arctica* shells in the bycatch were investigated, shell length measured, and proportions of empty and damaged *A. islandica* documented.

The weight of total catch was measured on board using a Marel scale (M 1100, accuracy 0.1 kg). Length of *A. islandica* was measured by caliper to the nearest millimeter and the number of total and damaged individuals recorded. State of individuals was checked by manually applying pressure on both valves in order to slide and displace those. If the animal withstood, they were classified as “living”. In the lab, animals were blotted and weighed in total and individually (fresh mass) in the evening of the same day (accuracy 0.01 g). We recorded the approximate area of shell damage in each individual and location of damage (location options considered were umbo, posterior end, anterior end, and margin).

2.2 Fehmarnbelt

Additional bycatch data from scientific bottom otter trawling undertaken in 2020 farther north in FB (Fig. 1) – under similar fishing conditions (same gear and towing speed) – were also taken into account for this study. However, the 2020 bycatch was not analyzed in the same detail as in 2024. In 2020 simply the “total *Arctica* bycatch” or “living *Arctica*” in the bycatch were reported from the otter trawl fishing, and these numbers are available only as percentages (Tab. 1).

Two types of beam trawls were additionally performed in FB between 2020 and 2023. Three meter beam trawl hauls (mesh size: 20 mm, height: ~0.55 m; n = 33 hauls, Tab. 1) and 2 m beam trawl hauls (mesh size: 10 mm, height: ~0.45 m; n = 18 hauls, Tab. 1) and were investigated for “living *Arctica*” by recording the total mass of all individuals regardless of damaged or intact shells. In 17 of those 33 hauls “total *Arctica* bycatch” was also noted, which additionally includes empty shells. Only 6 hauls were anaylzed for damage and can be reported as percentage of the number of individuals retrieved in bycatch. Dredge hauls taken with “Kieler Kinderwagen” dredge (1 m; 3 x 3 mm mesh size) (Rees, 2009) were analyzed in FB (RV *Elisabeth Mann Borgese* cruise EMB238) in June 2020, but only with respect to damaged versus total *A. islandica* individuals collected alive.

For comparison with the natural abundance and biomass of *A. islandica* at the otter trawling site off Kühlungsborn, we took van Veen grab samples (0.1 m², n=4). Samples were sieved onboard using a 1 mm sieve and material was fixed in a 4% seawater-formaldehyde solution buffered with marble chippings. In the laboratory, organisms were counted and weighed to determine abundance and biomass per square meter. Ash-free dry mass (AFDM) was estimated from fresh mass (FM) using conversion factors from Gogina et al. (2022).

To characterize the population structures we measured shell length to the nearest millimeter and reported the data as 5 mm size classes. To examine habitat properties and characteristics, large mobile species and epifauna, as well as to visualize the effects of disturbance, the underwater video transects were carried out before and after trawling on bord RV *Elisabeth Mann Borgese* with a hand-held SeaViewer Sea Drop 6000 HD underwater video systems with mounted GoPro HERO5 Black camera (the two cameras, SeaViewer and GoPro, are intended to capture the seafloor at different angles). The camera system was usually towed approximately 0.5 m above the seafloor with a speed of 0.5 knots.

3 Results

In 2024, the three otter trawl hauls of MB provided a total of 322 living *A. islandica* individuals (that constituted 12.5 kg FM), of which 25 individuals were damaged*.* The total empty shell mass was 12.5 kg, including 8.5 kg shells with both valves still connected (n = 1047, data not included in Tab. 1). Accordingly, there were almost four times more empty *Arctica* shells and thus remains of dead individuals (1255, if the remaining not connected individual valves are accounted for) in the bottom trawl as living animals. Thus, empty shell mass equals that of the living *Arctica* biomass. Empty shells were not counted in earlier fishing events (Tab.1); however, they were also observed in 2021 in a first *in-situ* experiment (RUNKEL 2022; FORSTER et al. 2023, Fig. 1). At the study site, we found a massive accumulation of empty *Arctica* shells in the mound area compared to furrow generated by the otter board as well as compared to control areas. The three hauls in 2024 contained between 2 and 20 kg total bycatch, thereof 1.5 – 9.4 kg were living *Arctica islandica*. Only few of the living ocean quahogs were damaged (1 – 24). These numbers are equivalent to 0.0014 (± 0.0012) living individuals/m² which were hauled on board during the fishing process, while the mean of damaged individuals was 0.00011 (± 0.00018) individuals/m².

Compared to otter trawls, damage in beam trawl hauls in FB, an area with higher *Arctica* abundance, was more pronounced. In these beam trawls *Arctica* bycatch accounted for approximately 38% of the total catch weight, compared to 2 – 17 % in otter trawl hauls. In these trawls, damaged *Arctica* individuals had a proportion 8 – 65 % in six 3 m beam trawls versus 0 – 11% in otter trawls. Dredge deployments contained only 3% of damaged individuals.

Tab. 1 Total bycatch of *A. islandica* (numbers, biomasses [fresh mass, FM]) on 20 July 2024 in the area of the field trawl experiment II as well as north of Fehmarnbelt (FB) with different gear (bottom otter trawl TV3-520; beam trawl 3m and beam trawl 2m; dredge) in 2020, 2021 and 2023. na: not available. In column 5, total Arctica bycatch, n denotes the number of beam trawls and dredges. Percentages relate to total catch mass, except for damage where percentage relates to the number of living individuals. *: data from Werner (2021). #: Haul 1 and 2 were analyzed completely while a subsample of 62% in haul 3 was processed.

Date/cruise#	Gear type	Swept area [m²]	total catch [kg FM]	Total *Arctica*-bycatch [kg FM]	Living [kg FM]	Shells [kg FM]	Living/ damaged [n/n] (% damaged)
Experimental site MB							
20.07.2024/ CLU 389, haul 1	otter trawl	83 340	126.6	2.8 (2.2 %)	1.6 (1.2 %)	1.2 (1.0 %)	54/1 (1.9 %)
20.07.2024/ CLU 389, haul 2	otter trawl	66 672	111.7	2.1 (1.9 %)	1.5 (1.3 %)	0.6 (0.6 %)	49/0 (0 %)
20.07.2024/ CLU 389, haul 3 #	otter trawl	77 784	288.8	20.1 (7.0 %)	9.4 (3.3 %)	10.7 (3.7 %)	219/24 (11 %)
23.05.2020/ CLU343	otter trawl		200	33.5 (17.0 %)	na	na	na
14.07.2020/ SB777	otter trawl		198	na	7.5 (4 %)	na	na
Fehmarnbelt				(Percent)			
07_2020/01_2021/ 01_2023/ CLU 343, 351, 374, 05_2020/SB777	beam trawl (3m)		3.2 – 92.2	na (39.2 ± 15.4 %) n = 17	na (10.9 ± 7.3 %) n = 33	na	1005/196 (7.9 – 65.3 %) n = 6*
07_2020/01_2021/ CLU 343, 351, 05_2020/SB777	beam trawl (2m)		2.7 – 48.8	na (37.8 ± 11.2 %) n = 17	na / (6.7 ± 11.2 %) n = 18	na	195/77 (39.5 %) n = 1*
06_2020 EMB 238	dredge (Kieler Kinder-wagen) (1m)						381/15 (3.2 %) n = 3*

Approximately 11% of the living *Arctica* bycatch in haul 3 (MB) of 2024 (n = 219) were damaged (Tab. 1). Averaging hauls 1 – 3 shows that ~ 4% of the living bivalves were damaged, most of them with damage affecting ≤ 50% of the shell area (Fig. 2). Damage of the shells occurred predominantly at the umbo or in the area of maximum thickness of the animals, as was also apparent in other samples including beam trawls, dredge and otter trawls. Damage at the edges, as seen in the middle top row of Figure 2, was rare.

Fig. 2 Examples of shell damage found in bycatch from bottom otter trawl (experimental site off Kühlungsborn Mecklenburg Bight, July 2024).

Size distribution in the net hauls in the experimental study area of MB included only individuals above ~20 mm length. Van Veen grab samples (1 mm mesh size) in this area revealed that larger individuals are dominat within the population. Even in these samples no ocean quahogs with shell lengths below 20 mm were caught (Fig. 3, left). Moreover, this dominance of higher length classes is also visible in FB (grab samples) with a slightly higher maximum at 50 – 55 mm length class (Fig. 3, right).

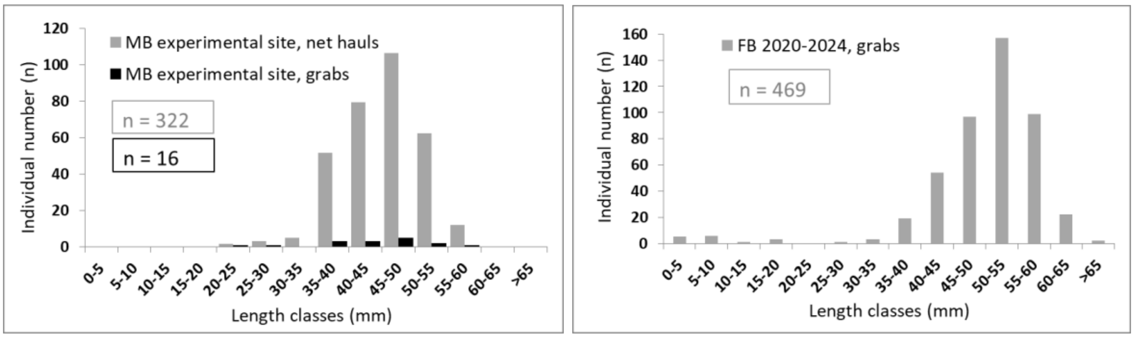

Fig. 3 Length distribution of living *Arctica islandica* fished in three bottom otter trawl hauls and in the natural population sampled by van Veen grabs of the experimental site (left). Additionally, the natural size structure from Fehmarnbelt area is shown (van Veen grabs only) (right).

In the 2024 experimental area of MB, *A. islandica* was present only in 28% of the grab samples (in 10 out of 36 samples collected), but if present – it constituted between 86 and 99% of the macrofauna biomass (and only 1.4 to 11.1% of abundance). Overall, abundance estimated based on grabs collected before trawling (including those without *A. islandica* individuals) was 10 ± 8 ind/m^2 and AFDM 7.2 ± 6.8 g/m^2.

4 Discussion

Here, we illustrated the different effects of bottom trawling on *A. islandica* depending on the fishing gear. Since a variety of different gear types are used by commercial fisheries, the results are not generally transferable to the impact of commercial fishing on *Artica islandica*. However, due to similar fishing techniques the mechanical impact might be similar between gears and it can be assumed that commercial fishing can have an impact on the population of *A. islandica,* yet, the extend remains unknown. Here, we focus on the amount of *A. islandica* retrieved in the trawl net from the seafloor, the process of hauling and lifting the net onto the ship as well as the conceivable consequences and fate of discarded bycatch. Any damage caused to the seafloor and organisms therein by ropes, chains and roller gear are not included in the present discussion.

Our experimental study was conducted in the area located in the habitat type AB.H3L3 ‘Baltic aphotic muddy sediment dominated by ocean quahog (*Arctica islandica*)’, as defined by the HELCOM Underwater Biotope and Habitat classification system (HELCOM, 2013). Covering an area of approximately 1418 km², this habitat occupies 9.2 % of the German western Baltic Sea floor area (Fig. 1, MARX et al. 2024). Our study area is similar to FB in terms of grain size and organic content and other key stations in MB and is characterized by similar and rather typical populations of *A. islandica* (ZETTLER et al., 2001; SCHULZ et al., 2025): old animals dominate, middle size classes (10 and 30 mm) are sometimes completely absent, and juvenile bivalves occur sporadically, indicating an irregular recruitement (data not shown). This irregular recruitment and various pressures, such as temperature increase, O_2 deficiency, and fisheries with mobile bottom-contacting gears, continue to threaten this species or may even increase the endangerment.

Selective sampling through mesh size of fishing gear, e.g., 20 mm in otter and 10 mm and 20 mm in beam trawls, constrains our bycatch observations to older animals above 10 to 20 mm shell length (Fig. 3). Despite this bias, our observations essentially reflect the *in-situ* population, since this population is also currently dominated by large individuals throughout most parts of the MB.

Our results show that at the experimental study site north of Kühlungsborn around 4 % of the bycatch ocean quahogs (on average) were severely damaged by the bottom otter trawl. The number of damaged *Arctica* roughly correlates with the total catch with highest damage in the largest catch (Tab. 1). A possible process explaining this observation may be the higher pressure imposed on bivalves if a more massive catch is lifted onboard. Previous results by RUMOHR & KROST (1991; 10.6%) indicate higher percentage damage (but match the largest values observed in our study). The difference may be due to methodology, region or varying population structure in years when the research was conducted. Furthermore, the combination of otter boards directly in front of a “Kieler Kinderwagen” dredge (1 m) sampling the bivalves may include individuals mechanically damaged by the boards. In our current setting the distance between otter boards and net is an order of magnitude larger than in RUMOHR & KROST (1991) and the net is laterally displaced relative to the boards. Therefore, inclusion of bivalves mechanically damaged by the otter boards in our net is unlikely. Comparing their and our dredge results, our low value of 3.2 % damaged individuals may indicate that individuals in fact damaged by otter boards were included in their dredge, or their total *Arctica* catch was higher imposing more pressure to the bivalves (see below). Beam trawls in general seem to produce more damage than otter trawls with an average of 26 ± 22 % (n = 6, Tab. 1) (WERNER, 2021).

Although damaged *Arctica* individuals were observed in two (haul 1 and 3) out of three TV3-520 trawling hauls, their number as well as total number of individuals removed during trawling is low relative to the *in-situ* abundance. Assuming an abundance of 10 ind./m², 0.014 % (± 0.012) of the total number of ocean quahogs in the swept area were removed by the otter trawl net. The percentage of animals damaged during the process compared to those assumed to inhabit the swept area based on the assumption above is even smaller: 0.0011 % (± 0.0017) or 25 individuals out of approximately 2,278,000 individuals being damaged.

Thus, our result suggest little impact, however, this study does not comprise all the damage potentially inflicted on *A. islandica* during bottom trawling. In addition to the information on potential mechanical damage to *A. islandica* by mobile bottom-contacting fishing as bycatch given here, there are also other aspects, such as direct effects of bottom trawling on juvenile *A. islandica* at the seabed (BERGMANN & VAN SANTBRING, 2000).

In commercial fisheries, the bycatch of benthic invertebrates is routinely discarded and ends up on the seabed. Depending on the time spent on deck, exposed to air and thus potentially adverse high or low temperatures, some of the bivalves that are not damaged will still die. The fate of those individuals surviving once they reach the seabed is unknown. Cod (*Gadus morhua*) may more easily find the individuals exposed on the sediment and feed on them (in earlier decades feeding on *A. islandica* was reported even for larger cod (see BAGGE et al., 1994 and references therein). The common starfish (*Asterias rubens*) also inhabits the area and is often observed preying on *A. islandica* (Fig. 4). Damaged *Arctica* most likely do not survive, because benthic predators are numerous (Fig. 4) and *A. islandica* cannot repair shell damage except when injuries are small or at the shell edges (e.g., WITBAARD & KLEIN, 1994). Earlier investigations and video footage from our study show that intact *Arctica* and its shells are often found in accumulated patches on the seafloor (Fig. 5, 6). Similar patterns were observed in Fehmarn Belt and described in ARNTZ & WEBER (1970) for Kiel Bay, indicating that such accumulations could be a recurring feature in areas influenced by fishing activity.

Fig. 4 Starfish (*Asterias rubens*) actively preying on *A. islandica,* shell is open, a flatfish is also partially seeing buried in the near sediment (left); starfish has captured and enveloped the clam (right), showcasing specialized feeding behavior through external digestion (© Dr. M. Gogina, IOW).

HIDDING et al. (2019) found a relation of benthic invertebrate species longevity on the effect of bottom trawling which they related to slower recovery rates in the long-lived biota. *A. islandica* is a long living species with reported ages up to 40 years in the Baltic Sea (ZETTLER et al., 2001; SCHULZ et al., 2025). Whether there is an effect related to the longevity of this species in FB and MB cannot be deduced from these data. Bottom trawling fisheries has been high throughout several decades in the FB and MB (ICES, 2019; ICES, 2022), therefore we would anticipate more large individuals in an *Arctica*-population without any fishing pressure. Direct evidence for an existing fishery effect may only be found once bottom trawling ceases. Main commercial fisheries using bottom trawls in the Baltic Sea were targeting cod, but due to the poor condition of the Western Baltic cod stock, the fishery targetting cod is closed, followed by a substantial decrease of fishing effort in the last years though fishery targeting flatfish continued. In some areas, fishing with mobile bottom-contacting gears has been fully prohibited since November 2024. It now remains to be seen to what extent the size and age structure of the *Arctica* population will change over the next years and decades. However, due to the typically patchy recruitment in the region, it is fundamentally difficult to delineate changes related to natural variability from those caused by altered human use.

We further speculate about the mechanism of shell breakage close to the umbo. We assume that the forces are greatest at the broadest part of the shell when these are pressed against each other or against other hard surfaces. In the Baltic Sea the inner shell layer of *A. islandica* may be reduced as a consequence of recurring hypoxia (SCHÖNE, 2013). This could be an additional explanation for the observed damage at the broadest part. WITBAARD & KLEIN (1994) reported a different pattern of damage in empty shells from the North Sea where valve thickness is likely not reduced. Here the posterior area in the shell was predominatly affected by beam trawls, indicating damage while the animals were in their life position in the sediment, possibly by tickler chains or similar parts of the gear. In our samples this pattern was not observed indicating that damage patterns depend on both gear type and the stability of valves in different environments.

The results presented here indicate that different gear types result in different degrees of damage to *A. islandica.* In beam trawls, *Arctica* bycatch had the highest proportion and fewer fish were caught than in bottom otter trawls. We assume that the greater probability of shells touching each other during hauling leads to greater forces pressing the shells against each other in beam trawls. Conversely, in bottom otter trawls the soft tissue of proportionally more fish acts as a buffer between the individual shells and reduces point pressure. Thus, we anticipate that much of shell damage in our data occurred during hauling, likely when the net emerged from the water. Alternatively, subject to the position of the specimens in the sediment, the chain net employed in beam trawls, which is absent in otter trawls, caused additional damage (in line with EIGAARD et al., 2016).

Fig. 5 (Left) Accumulation of *Arctica* shells and predatory *Asterias rubens* and *Ophiura albida* in the Fehmarnbelt at a water depth of 23 m (06_2020, EMB238). (Right) Accumulation of *A. islandica* and empty *Arctica* shells in the area of field experiment I (06_2021, EMB268). Both images (© Dr M. Gogina, IOW) presumably show discard areas of bycatch from bottom trawl hauls.

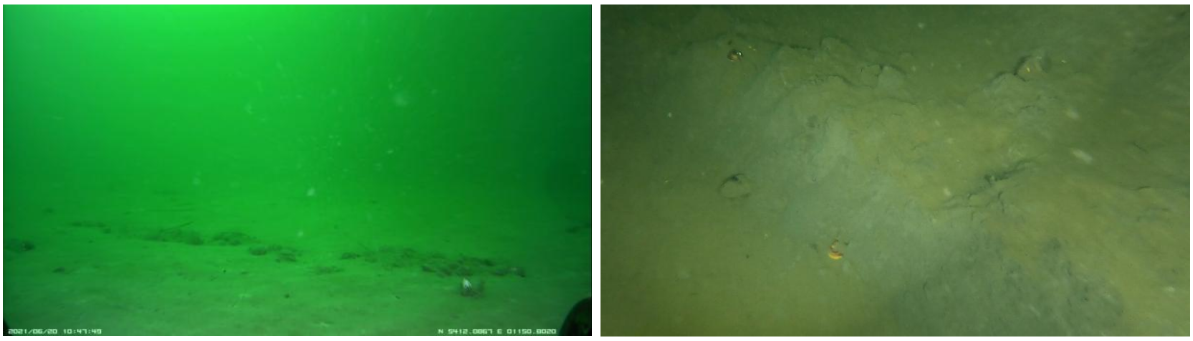

Fig. 6 *Arctica islandica* in an ”unnatural“ in-line configuration on the sediment presumably in the mound area of a former trawling mark in the area of field experiment (06_2021, EMB268) (© Dr. M. Gogina, IOW).

Numerous empty *A. islandica* shells are commonly found within accumulated patches of intact *A. islandica* and its shells found in muddy habitats of our investigation areas (Fig. 5, 6). Notably, shell damage as described here (Fig. 2) is rarely observed, suggesting that many of these empty shells were not mechanically crushed. These remains could originate from fishing discard, representing undamaged individuals that may have died due to stressors associated with trawling, such as abrupt pressure changes, mechanical impact during hauling or prolonged aerial exposure on deck. Alternatively, the presence of intact shells could also reflect *in-situ* mortality caused by natural predation, where predators (such as sea stars, gastropods or fish) consume the soft tissue without damaging the shell. Distinguishing between these scenarios remains challenging but is critical for interpreting benthic mortality patterns. In any case dead *Arctica* shells that may originate from discard could potentially enhance carbon storage.

During the towing process, macrofauna organisms living in the sediment, and particularly the biomass-dominating *A. islandica* may be displaced onto the sediment surface by the bottom otter boards, as images showing “unnatural” in-line accumulations of *Arctica* individuals suggest (Fig. 6). It remains unclear to what extent this process may also lead to mechanical damage of their shells (see above), and thus to increased mortality. During trawling, however, mostly empy shells are mechanically aligned on the sea floor. This effect appears to be less pronounced for living individuals (RUNKEL, 2023), likely due to their ability to burrow and move horizontally.

The fact that alignment or clustering does take place may explain a seemingly counterintuitive observation in the area. In a recent study, *A. islandica* biomass was shown to increase where fishing activity was higher (ACKERMANN, 2024). If towing and discarded bycatch promote the formation of clusters of living individuals, animals are no longer evenly distributed across the seafloor and the patchy distribution may cause higher bias in abundance estimates. Routine sampling efforts can therefore undersample and misestimate the true variability in spatial distribution. Since significant increases in *A. islandica* biomass under high fishing intensity was not observed in abundance data (ACKERMANN, 2024), the observed effect of biomass increase may also be driven by few large individuals. This suggests that additional abiotic factors such as salinity and food availability, differing where trawling was more intense, strongly shape benthic community structure, complicating efforts to directly link observed patterns to trawling effects alone.

To conclude, the impact of bottom trawling on *A. islandica* can vary by gear type with highest effect in beam trawls (which are not allowed in commercial fisheries in the Baltic) and handling processes; while direct mechanical shell damage appears low (~ 4 % of bycatch), indirect effects during hauling and discard likely contribute to delayed mortality and alter the population structure. Although immediate mortality appears minimal, cumulative effects from repeated disturbance, exposure during discarding and vulnerability to predators, combined with long lifespan and irregular recruitment of this species, suggest that intermediate and long-term population impacts cannot be ruled out.

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