frontiers | Frontiers in Marine Science

TYPE Brief Research Report
PUBLISHED 07 October 2022
DOI 10.3389/fmars.2022.981840

OPEN ACCESS

EDITED BY
Daniel Rittschof,
Duke University, United States

REVIEWED BY
Joanne Edney,
Southern Cross University, Australia
Winnie Courtene-Jones,
Scottish Association For Marine Science, United Kingdom
Mufti Petala Patria,
University of Indonesia, Indonesia

*CORRESPONDENCE
Andrea Stolte
andrea.stolte@wwf.de

SPECIALTY SECTION
This article was submitted to Marine Pollution, a section of the journal Frontiers in Marine Science

RECEIVED 29 June 2022
ACCEPTED 07 September 2022
PUBLISHED 07 October 2022

CITATION
Stolte A, Dederer G, Lamp J, Fenn C, Lee M, Frank W, Howe C, Günther M, Vesper H and Werner S (2022) The quest for ghost gear in the German Baltic Sea: A team effort between WWF, divers, fisherfolk, and public authorities.
Front. Mar. Sci. 9:981840.
doi: 10.3389/fmars.2022.981840

The quest for ghost gear in the German Baltic Sea: A team effort between WWF, divers, fisherfolk, and public authorities

Andrea Stolte[1]*, Gabriele Dederer[1], Jochen Lamp[1], Crayton Fenn[2], Mareen Lee[3], Wolfgang Frank[4], Christian Howe[5], Michael Günther[6], Heike Vesper[7] and Stefanie Werner[8]

[1]Baltic Sea Office, Department of Marine Conservation, WWF Germany, Stralsund, Germany, [2]Fenn Enterprises, Mountlake Terrace, WA, United States, [3]Department Marketing Online, WWF Germany, Berlin, Germany, [4]Divebase Prora, Proraer Chaussee, Binz, Germany, [5]Submaris Scientific Diving, Kiel, Germany, [6]Independent Consultant, Jena, Germany, [7]International Centre for Marine Conservation, WWF Germany, Hamburg, Germany, [8]Federal Environment Agency (Umweltbundesamt UBA), Department of Marine Conservation, Dessau-Roßlau, Germany

In this pilot project, World Wild Fund for Nature (WWF) Germany works together with regional divers, fisherfolk and public authorities to reduce the impact of lost fishing gear in the Baltic Sea. If not removed, ghost gear poses a threat to the marine environment and wildlife including seabirds, seals, harbour porpoises and fish. Over decades to centuries, lost fishing nets and ropes shed microplastic fibres into the marine environment. Removing this hazard reduces both the risk of entanglement as well as the contamination of the marine foodweb through ingestion of microplastics and associated chemicals. Identifying lost fishing gear in the marine environment poses one of the largest challenges impeding mitigation through gear retrieval operations. Lost gear can be drifting on the surface, in the water column, or can be sunken to the seafloor as a result of material composition, fouling, and entanglement. In the Baltic Sea, ghost gear is located on the seafloor and not visible during visual surface surveys from vessels. Identifying an efficient search methodology was therefore a key aspect of WWF's ghost gear project. After trials with different search and retrieval methodologies, WWF Germany found sonar search technology to be the most efficient technique to locate lost gear on the seafloor. Sound waves avoid the limitations faced by divers or visual cameras in low-visibility environments, and a substantially larger area can be covered. In contrast to diving teams focussing on wreck retrievals, the many nets lost on the seafloor remain unnoticed by divers under most circumstances. A combination of sonar search providing exact GPS positions of suspect ghost gear, diver verification through the WWF Ghostdiver App, point-on retrievals with fishing vessels, and manual sorting for waste management provides an

efficient methodology for long-term political implementation of regular lost gear retrieval campaigns.

KEYWORDS

lost fishing gear recovery, sonar search technology, marine plastic litter, hazardous waste, microplastics, abandoned, lost or discarded fishing gear (ALDFG)

Introduction

Lost fishing gear is omnipresent in the seas worldwide. Yet the fractions of fishing-related litter such as nets, ropes, lines and pots differ among the amount of plastic litter observed in the marine environment. In the Northeast Atlantic region, Pham et al. (2014) find between 25 and 30% of plastic litter items on the seafloor and near the surface originating from fisheries. In a recent review, Galgani et al. (2015) report up to 89% of seafloor litter in the Atlantic Ocean to originate from the fishing sector. On the surface of the Great Pacific Gyre, Lebreton et al. (2018) identified 46% of plastic items being composed of nets, ropes and lines. Increasing fractions of beach litter items are composed of fisheries plastic waste when progressing north into the Arctic regions of Europe, with as much as 80% of beach plastic litter originating from fisheries on beaches around Spitsbergen, including heavy fishing nets, ropes, and buoys/fenders (Bergmann et al., 2017).

Even in small numbers, abandoned, lost or discarded fishing gear (ALDFG, UNEP/FAO definition: Macfadyen et al., 2009), commonly called "ghost gear", can cause substantial harm through entanglement and ingestion (Kühn and van Franeker, 2020, and references therein, Werner et al., 2016). Between 2,000 and 12,000 tonnes of fishing gear waste are estimated to enter the European seas each year (Sherrington et al., 2016). The amount entering the Baltic Sea alone is not known, although Predki et al. (2011) estimated between 150 and 450 tonnes entering the Baltic each year from the more extensive fishing effort in the early 2000s. Globally, fishing gear causes entanglement of both commercial and endangered species, and is frequently reported in the media for large cetaceans, e.g., in the Mediterranean where both entanglement in and ingestion of ropes and netting is observed (Fossi et al., 2018). In their recent review, Kühn and van Franeker (2020) find that at least 354 marine species are impacted by entanglement, with 27.4% of seabird species, 39.8% of marine mammal species (71% when seals are considered alone), and all 7 marine turtle species. Although no scientific study was identified for the Baltic Sea, entanglement in ALDFG might affect harbour porpoises, grey and common seals. Stranded whales are occasionally found to contain bundles of netting or ropes in their stomachs, which might have prevented natural feeding activity (Jacobsen et al., 2010). From our observations, entanglement of species in ALDFG in the Baltic Sea is rare in comparison to the impact of active fishing gear, because lost trawl netting made from nylon is bundled up on the seafloor. The dominant source of ALDFG lost in German Baltic waters according to participating fishers today are gillnets, which are considered one of the most hazardous forms of ALDFG (Gilman et al. 2021; Global Ghost Gear Initiative, 2021). Seabirds such as two cormorants and two long-tailed ducks were found in retrieved gillnets in two different locations (Figures 1A, B), where one of the cormorants became entangled within less than 6 days between the ghost net discovery and retrieval. Both gillnets had been overgrown with algae and contained fish skeletons as well as fresh fish and birds, suggesting they had been trapping fauna in the sea for several months.

On sensitive seafloor habitats, smothering degrades the ecosystem. While this has not been investigated in the Baltic Sea, severe disturbance of benthic communities and biogenic reefs are observed in the Mediterranean and Asian coastal seas (Moschino et al., 2019; Kim et al., 2020). Over centuries (Thompson et al., 2004), ALDFG slowly degrades into microplastic fibres. These microplastic fibres are contained in sediments and the water column (e.g., Koelmans et al., 2017) and may be ingested by filter feeders and bottom-dwelling fauna. Microplastic fibres and particles in the marine food web are found to affect the smallest zooplankton down to a depth of 7000m (*Eurythenes plasticus*, Weston et al., 2020) to the largest filter feeders including the large whales in the Mediterranean and the Gulf of Mexico (e.g., Fossi et al., 2012; Fossi et al., 2014a; Fossi et al., 2014b). How much ALDFG contributes to the density of marine mircoplastics is not known. It is paramount to remove ALDFG where possible to mitigate these long-term impacts on the marine ecosystems. In the European Union, the Marine Strategy Framework Directive (MSFD 2008/56/EC) requires Member States to mitigate the impact of plastic litter on the marine environment. Political measures are devised for the Baltic Sea in the HELCOM (Baltic Marine Environment Protection Commission, https://helcom.fi) pressure group on marine litter (https://helcom.fi/action-areas/marine-litterand-noise/marine-litter) and for the North Sea by the OSPAR Convention for the Protection of the Marine Environment of the North-East Atlantic (https://www.ospar.org, https://www.ospar.org/work-areas/eiha/marine-litter).

10.3389/fmars.2022.981840

FIGURE 1
Impressions of WWF Germany's ghost gear project: **(A)** lost gillnet on the seafloor near Rostock still catching fish and seabirds (© Martin Siegel, WWF); **(B)** same gillnet ghost fishing for several months before its dicsovery with numerous plaice and two cormorants (© Wolf Wichmann, WWF); **(C)** diver verifying a sonar position to be a lost gillnet corresponding to Figure 2B (© Christian Howe, WWF); **(D)** professional diver retrieval of a trawl bundle mixed with other nets and litter (© Christian Howe, WWF); **(E)** the "UEK 12 Bergen" - typical Baltic Sea 17m fishing vessel used for pair trawls – and ghost gear retrievals (© Andrea Stolte, WWF); **(F)** fishers working hard on vessel "SAS 107 Crampas" to get sonar-identified lost gear on board (© Andrea Stolte, WWF); **(G)** gillnet retrieval in Wismar Bay with a 9m gillnetter (© Andrea Stolte, WWF); **(H)** retrieved trawl bundle during removal from the working vessel "Fritz Reuter" with a heavy lifting crane (© Christian Howe, WWF).

In this pilot project, WWF Germany works alongside fisherfolk to mitigate the impacts of lost fishing gear on the Baltic Sea ecosystem. For fisherfolk, gear loss is an economic burden as well as a hazard to fishing grounds. Entanglement in gear lost during previous fishing sets multiplies this hazard, retrieval operations are costly, and catch in ALDFG is lost for commercial use (Brown and Macfadyen, 2007; Mouat et al., 2010; Newman et al., 2015; GESAMP, 2021 and references therein). As an inward sea, any litter entering the Baltic has no escape route. In the 1960-70s, the so-called "cod boom" led to an extensive trawler fishing fleet with a peak of 103 high-sees trawlers in Eastern Germany alone (http://www.rostocker-hochseefischerei.de/schiffe/schiffe.php). GPS positions of wrecks and other obstacles were not available at the time, and conflict between different fisheries can be assumed more common, and – with fishers still used to natural fibre materials - discarding of end-of-life nets before returning to port was not yet considered a problematic practice for the marine environment. Most of the 24 tonnes of ALDFG retrieved during this pilot project were historic netting recovered in the vicinity of Sassnitz harbour, which was one of the largest fishing ports of Eastern Germany. During a similar pilot project in 2015, WWF Poland retrieved 270 tonnes of trawl netting from offshore fishing grounds in Polish waters (WWF Poland, private communication). As ALDFG is one of the most harmful plastic litter for flora, fauna and habitats (Werner et al., 2016), WWF engaged in the development of a methodology that can lead to political implementation of lost gear mitigation measures through state authorities.

Globally, other initiatives such as the Global Ghost Gear Initiative (https://www.ghostgear.org), ghostdiving (https://www.ghostdiving.org), and many smaller, private organisations collect lost fishing gear from sensitive seafloor habitats worldwilde. One of the longest projects is carried out by the Northwest Straits Foundation in Puget Sound, USA, where since 2002, more than 5.800 nets and 6.000 crab pots were removed (https://nwstraitsfoundation.org/derelict-gear). This project utilises sonar technology developed by Fenn Enterprises since more than 25 years, which led to the collaboration for the method development in the German Baltic Sea detailed below. The longest-standing government-led project is organised by the Norwegian Fisheries Directorat since the mid 1980s, where fisherfolk are involved in the retrievals of deep-set gillnets and lobster pots in Norwegian fjords to conserve both the sensitive rocky habitats and the fishing grounds (https://www.fiskeridir.no/English/Fisheries/Marine-litter/Retrieval-of-lost-fishing-gear). In the Baltic Sea, the most consolidated initiative devising lost fishing gear mitigation measures so far was the MARELITT Baltic EU INTERREG project (2016-2019) with partners from four countries, Estonia, Germany, Poland and Sweden, in which WWF Germany was the partner on the German side (https://marelittbaltic.eu).

Since 2014, WWF Germany has developed a methodology to search for, retrieve and find a waste-management solution for lost fishing gear from the Baltic Sea. The pilot project was enabled by private-sector partnerships, the European Union Baltic Sea INTERREG programme, the German Federal Environment Agency, and other organisations (see Sec. 8 for details). From the beginning, WWF Germany was in close exchange with federal and state authorities to ensure a solution that can lead to longterm implementation. The project had several foci: 1) to ensure that mitigation activities reduce harm to the marine environment, 2) to engage local divers in the reporting of lost gear and encourage fisherfolk to participate in retrieval actions, and 3) to establish a method that can be used by state authorities for long-term mitigation of the impacts of ALDFG in the marine environment.

Developing a methodology to mitigate lost fishing gear in the Baltic Sea

Upon gear loss, fisherfolk employ steel hooks, small anchors, or chains with weighted hooks to search for and retrieve the lost gear (Predki et al., 2019, Figures 13,14). When the exact position of gear loss is unknown, this method can be unsuccessful and cause damage to the seafloor habitat. Initially, trials were made using such "search hooks" as employed by fishers to recover gear in the Baltic Sea with knowledge of historic loss hot spots from the fishing sector. This "semi-blind" search, focussing on pre-selected gear loss hot spot areas provided by regional fisherfolk, and the small area coverage with search hooks proved highly inefficient. The ecological impact of these operations has to be considered, as bottom-touching area searches have impacts on the seafloor habitat (Sahlin and Tjensvoll, 2018). Worldwide and in the Baltic Sea, recreational and tech diving teams focus their valuable efforts on cleaning ghost gear from wrecks – both for the benefit of the marine fauna and for the wreck-diving experience. Cutting loose netting from wrecks is beneficial for marine fauna, as fish seek shelter near wrecks and seals and harbour porpoises follow prey, which leads to entanglement of both prey and predator species. In the first project year, WWF Germany cut loose 850kg of netting and ropes from wrecks in a week-long at-sea operation with a team of eight scientific divers. However, the work was physically challenging for the divers and the return for a large amount of effort was comparably limited. From our observations, a large fraction of fishing gear lost over decades in the Baltic Sea is located on the plain seafloor. For instance, the majority of the 24 tonnes of ALDFG retrieved by WWF near Sassnitz, Rügen Island, was located on the sandy seabed, including one trawl bundle with a single weight of 3 tonnes. This is likely due to a mix of discards being common practice several decades ago and netting carried by currents into the quieter, shallow bay areas. Some of these nets are snagged on

rocks or sunken anchors, while many are only marginally attached to obstacles or loosely lying on the seabed. With these different methods tested during the first project years, these nets were not discovered, such that WWF Germany decided in 2018 to follow another approach.

The most effective area-search providing environmentally sensitive identification of lost gear on the seafloor was found to be the search with sonar equipment (Figure 2A). High-resolution seafloor sonar scans are not bottom-touching and cover larger areas than is feasible by divers or searches with hooks. With a spatial resolution of a few centimeters, even gillnet sink- and swimlines are detected with side-scan sonar technology (Figures 2B–D). At the same time, sonar data deliver a large number of suspect positions that need to be verified by divers (Figure 1C). This confirmation is necessary to confirm suspect positions as real lost fishing gear or plastic ropes, verify exact GPS locations of the ghost gear and minimise the impact of the spot-on retrieval activity. WWF Germany has developed the "WWF Ghostdiver App" that engages divers in this verification process. Through the app, divers and other sea users can confirm sonar suspect positions in addition to regular reporting of lost gear encountered during independent diver activities. The description of the type and amount of material located on the seafloor, entanglement of animals and hence risk to marine fauna, snatching on obstacles, corrected GPS positions if needed, and images of the object on the seafloor can be transmitted through the app. In return, WWF receives the knowledge of which sonar objects are truly lost fishing gear, ropes and lines. Depending on the size and type (gillnet or trawl segment) of the identified object, this allows efficient retrieval operations with professional diving teams or fishing vessels for the exact type of lost gear that needs to be recovered from the seafloor. Over several years, a database of the amount of lost gear on the seafloor in selected fishing areas can be collected. Retrievals at exact GPS positions and with dedicated equipment avoid further damage of the seafloor and reduce the plastic pollution in the Baltic Sea.

After successful demonstration of the method, it is now the turn of German coastal state authorities to actively implement this measure into a longterm solution with the overarching aim to improve the environmental status of the Baltic Sea. The methodology and the WWF Ghostdiver app can readily be adapted to other sea regions and are presently tested in the Mediterranean.

Methods

WWF Germany has developed environmentally sensitive methods to search for, retrieve and waste manage ALDFG from the Baltic Sea. Being too small to develop lunar tides, the Baltic Sea provides the ideal testing ground with diving times exclusively depending on water depth. In tidally dominated

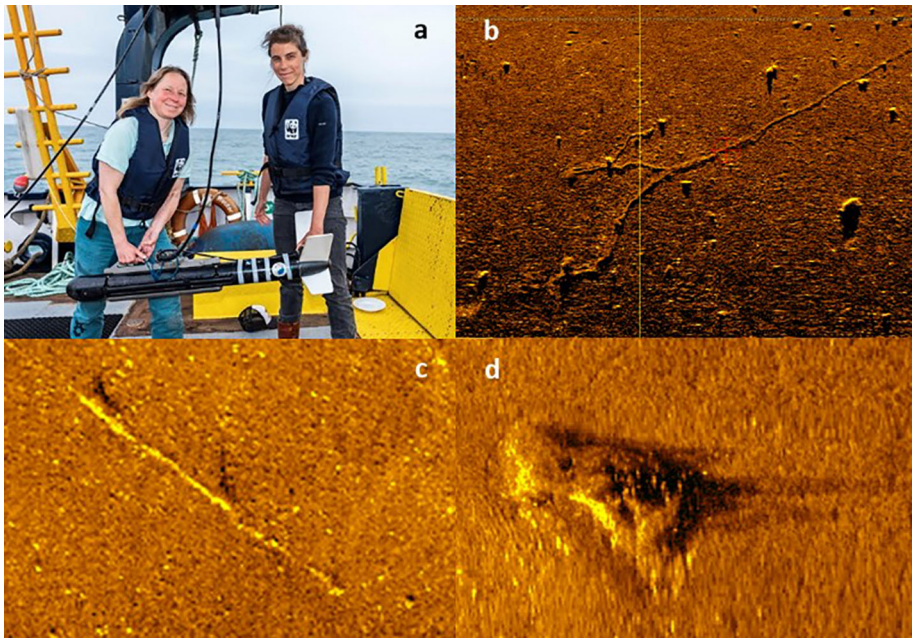

FIGURE 2
Search success using sonar technology: **(A)** project managers Andrea Stolte (left) and Gabriele Dederer (right) before deploying the sonar fish (© Uli Kunz, WWF); **(B–D)** examples of sonar images of two gillnets and one trawl bundle showing its height above the seafloor by its extended sonar shadows (© WWF Germany).

seas such as the North Sea, divers are limited to a narrow time window during the turning points of the tides to avoid the drag from tidal currents. As an inland sea only connected to the North Sea through the narrow straits of the Skagerrak and Kategatt, any pollution entering the Baltic is unlikely to escape into the North Sea or the wider Atlantic.

From the beginning of the project, fisherfolk, in particular trawlers, were employed for WWF retrieval activities and for search trials. Since March 2021, a pilot project is carried out with the support of the Environmental Ministry of Mecklenburg-Western Pomerania (MV). In this project, the key element is to employ some of the remaining fisherfolk to carry out search and retrieval activities at sea.

Search method: In 2018, WWF Germany adapted the sonar search technology for ALDFG developed by Fenn Enterprises and successfully applied by the Northwest Straits Foundation since more than 25 years in the Puget Sound (https://fennenterprises.com/projects). Towing a Marine Sonics ArcExplorer sonar fish with a transponder frequency of 600kHz as low as 5m above the seafloor at a speed of 3-4 knots, the obtained sonar spatial resolution of a few centimetres is sufficient to detect gillnet lines as thin as 1cm and other lines from trawl netting, as well as fish traps (Figure 2). This frequency is outside the hearing range of marine mammels. The swath width of 100m allows us to cover a much larger area in a few hours than could be searched by diving teams. Within the state pilot project, gillnet vessels are employed for sonar excursions in coastal fishing areas. The knowledge of present-day and historic loss areas of local fisherfolk is essential for defining sonar search areas.

Verification: Positions are visually identified during post-processing data analysis and need to be verified by divers. ALDFG suspect GPS positions are published in the WWF Ghostdiver App for verification (Figure 1C). "WWF Ghostdiver" also provides a communication platform to warn recreational divers from the risks of retrieving ALDFG from the seafloor.

Retrievals: Trawl netting is found in the Baltic Sea in large bundles weighing 1-4 tonnes each. Retrievals need to be carried out with fishing or working vessels hosting strong winches or cranes with 2-4 tonnes capacity (Figures 1D, H). Gillnets and traps are removed from shallow coastal waters (depth < 30m) with scientific divers. In contrast to recreational diving organsiations, which carry out the bulk of ghost gear retrievals worldwide on a volunteer basis, WWF retrievals are carried out with professional diving teams and not with recreational divers for efficiency and health risk minimisation. Since the beginning of the state pilot project in Mecklenburg-Western Pomerania, small 8-12m gillnetting vessels are involved in the retrieval of gillnet fragments (Figures 1G). For retrievals of trawl netting, 17m trawlers carry out the lifting of the netting from the seafloor (Figures 1E, F). In the first project year, five fishing companies were engaged for search and retrieval activities activities at sea, which is increasing in each of the two following project years.

Waste management: Recycling was found not to be viable for ALDFG retrieved from the seafloor in the Baltic Sea (Stolte and Schneider, 2018, MARELITT Baltic). Heavy contamination with organic matter, sediments, hazardous lead from sink lines and mixed plastics are prohibiting material recovery. Dismantling and cleaning are cost-, labour- and energy-intensive processes which might cause damage to machinery (Stolte and Schneider, 2018). In Germany, incineration is the only pathway for mixed plastic waste, after lead lines and metals are extracted manually for metal recycling.

Results

A map of all transects covered by the sonar survey is shown in Figure 3, with detailed results given in Table 1. A total of 326 suspect positions were identified in the German coastal state of Schleswig-Holstein (SH), of which 93 were verified until February 2022, and while 40 were ALDFG (success rate 43%), 53 were other objects or active nets (false suspect rate 57%, Table 1). In Mecklenburg-Western Pomerania, near Rügen Island, 83 of 223 sonar positions were verified with 54 ALDFG retrieved before December 2021. In a testbed area (Figure 4) near Neustadt, SH, after 3 days of sonar charting, 22 of 49 sonar positions verified during 5 diving days were confirmed as ALDFG, a success rate of 45%. All 22 nets could be retrieved within 9 recovery days with scientific divers. When all sonar data verified in both states so far are considered, the total success rate is 52%. The sonar success rate has to be compared to the blind search approach commonly used by fisherfolk after loosing a net, where a search hook is dragged over the seafloor in the area where the presumed loss occured. In the case of a trawl net, this can be hundreds of metres from the actual snagging point. In addition, nets lost or discarded decades ago cannot be located in blind searches unless vast areas of seafloor are covered with ground-touching gear, which is ecologically not warranted (Sahlin and Tjensvoll, 2018). Diver searches, on the other hand, focus on wrecks or on submarine structures. The sonar technology fills the gap to cover extended areas and re-locate lost gear in regions where divers are not active. Hence, a success rate of more than 50% is an excellent result for this approach. The 100m sonar swath with a total area of 4425 ha covered in Schleswig-Holstein in coastal fishing areas and 1395 ha in Mecklenburg-Western Pomerania in 45 days at sea, implies that an average area of at least 130 ha per day could be searched. This is a lower limit as no area estimation is available for the 7 days in 2018.

In comparison, scientific divers can search a circumference around a single, expected lost gear GPS position, or carry out a scooter search along a strip. In a circular area around a single point, a one-hour scientific dive covers a radius of approximately 30m and a search area of 2827m^2. Rounding this to 3000m^2, a day search with a rotating scientific diving team of four divers and six dives yields an area coverage of 18.000m^2, less than 2

10.3389/fmars.2022.981840

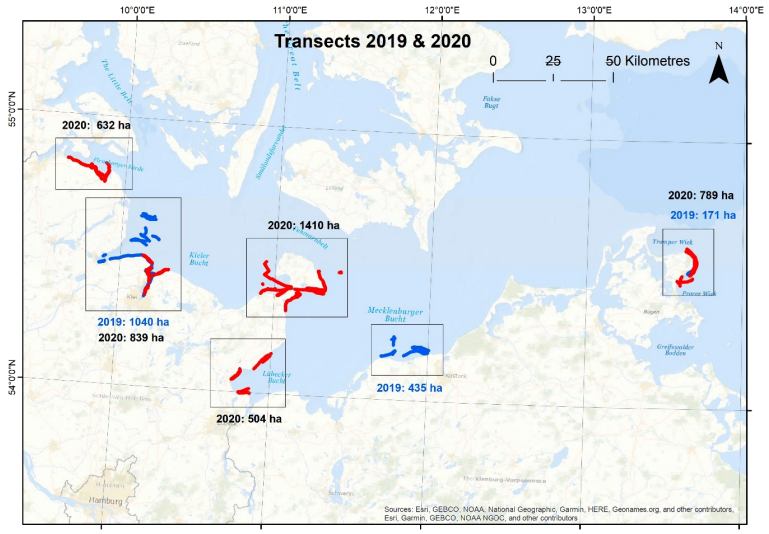

FIGURE 3
Sonar transects in the German Baltic Sea in 2019 and 2020. The area of each search region is given in hectars next to each regional box. The total charted area was 5820 ha on 45 days at sea, as summarised in Table 1. © Jutta Beher, WWF.

TABLE 1 Summary of pilot sonar searches and retrievals carried out during WWF Germany's ghost gear project in the years 2018 to 2021.

Search area	Sonar area (hectar)	Days at Sea	Sonar ALDFG suspect positions	Diver verification	ALDFG (retrieved)
Schleswig-Holstein (SH)					
Bay of Lübeck	504 ha	6	63	49	22 (20)
Fehmarn, Hohwacht Bay	1410 ha	5	61	17	7 (5)
Bay of Kiel & Eckernförde 2020	839 ha	7	56	16	4 (0)
Bay of Flensburg	632 ha	5	67	4	3 (3)
Total SH 2020	**3385 ha**	**23**	**247**	**86**	**36 (28)**
Bay of Kiel & Eckernförde 2019	1040 ha	5	79	7	4 (4)
Total SH 2019-2020	**4425 ha**	**28**	**326**	**93**	**40 (32)**
Mecklenburg-Western Pomerania (MV)					
Rügen Island 2020	789 ha	6	81	48	22 (22)
Rügen Island 2019	171 ha	2	70	29	28 (28)
Rügen Island 2018	–	7	70	6	4 (4)
Bay of Mecklenburg 2019	435 ha	2	2	0	0
Total MV 2018-2020	**1395 ha**[a]	**17**	**223**	**83**	**54 (54)**
Schleswig-Holstein plus Mecklenburg-Western Pomerania combined					
Total Sonar area	**5820 ha**	**45**	**549**	**176**	**94 (86)**
Efficieny / Average	**130 ha / day**			**Percentage of ALDFG among verified suspect positions:**	**52%**

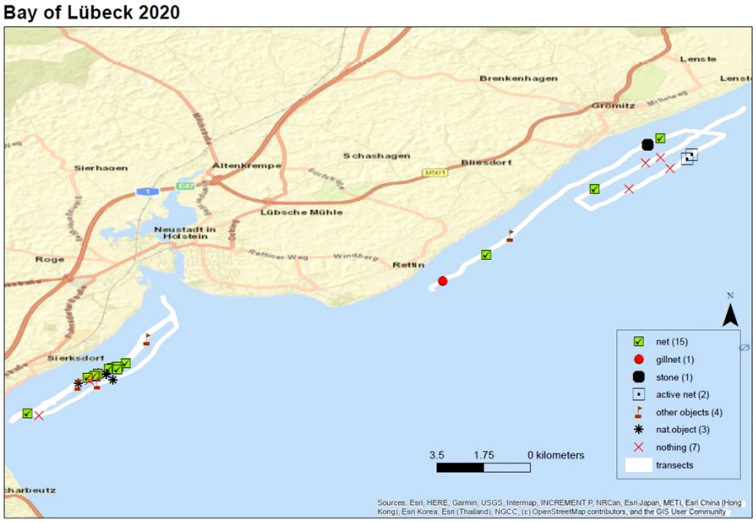

FIGURE 4
Test area in the Bay of Lübeck, with analysis of sonar supect positions, annotated with type of objects found at each suspect location. Sonar charting of 3 days led to 49 suspect positions in this test area, of which 22 were confirmed as lost gear or ropes on 5 scientific diving days. All 22 ALDFG could be retrieved on 9 days of recovery operations. © Jutta Beher, WWF.

hectares or just 1.5% of the average daily sonar area. During a scooter search, divers cover extended swathes. Assuming a strip length of 1km and visibility of 3m as an upper limit in the Baltic summer months implying a strip width of 6m, a single dive might cover 4 strips or an area of 24.000m^2. If six dives can be achieved, a total area of 14.4 ha can be covered in a single day during scooter searches. or just 11% of the average search area of 130 ha/day with the sonar, rendering the sonar charting followed by exactly positioned verification dives the most efficient search methodology. Sonar searches require a smaller team of 2-3 crew, compared to 4-5 members in a scientific diving team, and cover substantially more area, yielding economic benefits. The sonar is operated for 4-5 hours during a typical sonar cruise, implying an efficiency of 4.5h/130 ha or 2 minutes per hectar compared to 25 min/ha for 6 diving hours with scooters. Charter cost depends on vessel type, small diving or gillnetting vessels operate at lower charter and fuel costs than working or larger fishing vessels. Assuming a smaller vessel cost of at most 1000 Euros/130 ha results in a cost efficiency of 8 Euros per hectar. This cost has to be compared to a full scientific diving team with a maximum area coverage of 14.4 ha/day with scooters with at least 3 divers and a skipper, where professional costs depend on country and region and in Germany, are typically between 2000 and 4000 Euros/day or at least 140 Euros per hectar. The sonar search turns out to be 12 times more efficient in time and 17 times more efficient in cost than the diver search, in addition to the larger area covered by sonar charting. Even with a success rate of 50%, the chances are much higher to detect lost gear in fishing areas where exact loss positions are not known.

The ArcExplorer sonar and examples of ghost gear detection images are shown in Figure 2. The efficiency of the WWF methodology allowed 94 ALDFG to be retrieved from the Baltic seafloor during consolidated retrieval campaigns on accurate GPS positions. The 54 collected ALDFG in front of Rügen Island were comprised mainly of trawl netting, mixed with other forms of fisheries and marine litter, including metals, anchors, cables, tires, and gillnets (Figures 1D, F, H). While the focus of the state pilot project lies on retrieval with 9-17m class fishing vessels (Figures 1E-G), working vessels with heavy lifting cranes have to be employed for large trawl nets (Figure 1H). The total wet weight collected during the pilot project from 2014 to 2021 added to at least 24 tonnes. In Schleswig-Holstein, sonar searches were focussing on the coastal fisheries areas operating predominantly gillnets and traps. These smaller and lower-weight items were retrieved from the seafloor by scientific diving teams. While total weight estimates are not available for ALDFG collected in this coastal state, more than 2000m of gillnet fragments could be retrieved.

Discussion and limitations of the method

The methodology to search for and retrieve lost fishing gear from the Baltic Sea was developed to present a concept to state authorities, such as the Federal Environment Agency and the ministries of the German coastal states. In the European Union, all member states are required to achieve “good environmental status” under the Marine Strategy Framework Directive (MSFD

2008/56/EC). Cleaning actions to improve seafloor habitats and remove plastic litter as a longterm hazard to marine species are explicit measures implemented in Germany under the MSFD (BMUB 2016, Annex 1, p. 22). The Baltic Sea, in particular, is a marine environment under severe multiple stressors: temperature inrease as a direct consequence of climate change invokes oxygen-depleted zones potentially affecting fish nursery grounds (see Meier et al., 2022 for an in-depth review), enhanced by severe eutrophication from intensive agriculture causing algae blooms (Löptien and Dietze, 2022; Meier et al., 2022), contamination with toxins from ammunitions and other historic contaminants from at-sea disposal (Vanninen et al., 2020). The high density of shipping routes adds to the pressure on the ecosystem along with decades of intensive fishing without ecological consideration. Relieving the seafloor from lost fishing gear is a comparably low-cost measure to improve seafloor habitats without negative impact for any of the economic sectors, while providing benefits for the fishing sector. Incorporating the fishing sector for mitigation measures has the added benefit that fisheries contribute to the mitigation of longterm negative impacts caused by this industry. In Mecklenburg-Western Pomerania, a state-funded pilot project is already implemented with the aim to evaluate options for regular retrieval operations with fishing vessels. This community case study provides the foundation for the state projects outlined below and the insights necessary for its evalulation.

Despite the success in detecting and retrieving substantial amounts of trawl netting and gillnets, several challenges remain in the presented method.

Challenges of ghost gear in sonar data

The interpretation of sonar data is limited especially in areas with soft seabed habitats, where the sound penetration into the sediments delivers a similar reflectivity signal as a larger lost trawl net. Structured seafloors with rich underwater flora, but also natural structures such as edges and reefs can render data interpretation complex. Most coastal fishing grounds in the German Baltic Sea are located at depths of less than 15 metres, with typical depths of 8-12m. At present, WWF Germany has employed the sonar search methodology mainly in waters shallower than 25m, easy access for recreational and professional divers. The Northwest Straits Foundation and Fenn Enterprises are deploying sonar search technology down to depths of 200m and more in highly structured environments in search for ghost gear, e.g., in the North American Puget Sound (https://nwstraitsfoundation.org/derelict-gear, https://fennenterprises.com/projectsweath). With more than 25 years of experience, their detection rate for lost traps, pots and gillnets is very high. However, teams with less experience in the interpretation of sonar scan data cannot expect to obtain similarly high recovery rates.

Adaptation to other marine environments

In June 2021, WWF Germany in collaboration with the Federal Environment Agency has carried out a pilot search for lost fishing gear in the North Sea. In contrast to the Baltic Sea, high-density gillnet coastal fisheries do not exist along the German North Sea coast. The fisheries regions are much more extended and the swath width of 100m, covering substantially more area than diving teams could, becomes comparably small. No lost trawl netting could be identified in 8 days at sea during this pilot sonar search. The only places where ALDFG suspect positions were identified was 1) the Danish Limfjord, where intense recreational trap and gillnet fisheries spatially overlap with professional fishing activities, and 2) the rocky seabed near Heligoland Island, where one candidate gillnet or lobster trap line position was found in areas closed to professional fishing today, with only lobster pots still permitted. These positions could not be dived immediately due to tidal currents, and hence remain unconfirmed. The sonar scans of the seafloor down to 35 meters depth delivered excellent data quality under the tidal current conditions and in unfavourable weather with 1.5m waves. However, as hardly any ALDFG was found, it needs to be acknowledged that this search methodology has its limitations in extended fishing grounds where ALDFG hot spots are not known. This limitation has to be expected in other seas and ecoregions as well. Because the search area – though less limited in spatial coverage than diver or visual camera searches – with high-resolution sonar technology is limited to a swath width of 100 metres in the case of the 600kHz ArcExplorer, good knowledge of lost gear hot spots from regional fisheries is still a prerequisite for a successful and efficient search and retrieval campaign.

ALDFG as hazardous waste

Waste management remains problematic: ALDFG is delivered to a sorting facility in North Germany (Schleswig-Holstein) for dismantling and metal recycling. The organic and synthetic components are shredded for incineration. With the implementation of the revised European Port Reception Facilities Directive (EU 2019/883), collection of end-of-life fishing gear will be legal common practice in all fishing harbours. The producer responsibility scheme anticipated in the Single-Use Plastics Directive (EU 2019/904) provides a funding concept for waste management of all fishing gears brought into the European market. Both legislations serve to decrease the waste management problem, but do explicitely not account for actively retrieved ALDFG. For this hazardous waste, individual solutions will remain necessary.

WWF Germany's pilot project in the context of other retrieval campaigns

Lost fishing gear is retrieved by a wide range of organisations worldwide, mostly by recreational diving teams. Recreational divers have a strong motivation to keep their diving environment clean, as is evidenced e.g. by the PADI special course "Dive against debris" training divers in marine litter removal (https://www.diveagainstdebris.org). Ghostdiving.org offers dedicated ghost net retrieval trainings for experienced divers, as cutting nets or ropes from the seafloor harbours the risk of entanglement as a severe health risk for divers. For legal reasons, WWF is not entitled to work with recreational divers for retrieval activities because of liability issues. According to German labour law, even voluntary divers working in the context of a WWF-coordinated retrieval activity require insurance through a professional insurance organisation. More importantly, the method was developed to enable regular retrieval programmes by German environmental authorities to implement required measures for cleaner European Seas as set out in the Marine Strategy Framework Directive (2008/56/EC), where working with professional diving teams is required. Recreational divers play a key role in verification dives, where gear is observed but not handled. The WWF Ghostdiver App (see summary below) provides a public communication platform of positions and verification dives. Through verification dives, only confirmed lost gear positions are targeted with larger vessels, saving fuel, time and cost.

In the past years, several organisations, e.g., ghostdiving Germany, have removed nets, ropes and lines from wrecks. As was demonstrated in the first WWF project year, where 850kg of nets and ropes were cut from wrecks, this work is labourious and time-consuming, and the large amounts of lost trawls and gillnets on the seafloor cannot be captured in this way. A common database collecting the amounts of ghost gear retrieved is currently not available. Recreational and professional divers are encouraged to feed data into WWF's Ghostdiver App to monitor ghost gear locations and information, leading to a more complete picture of gear losses and retrieval success. WWF Germany highly values the effort of private organisations to clean ghost gear from wrecks and contribute to a safer, healthier marine environment in the Baltic Sea.

Comparison to North European ALDFG mitigation efforts

The MARELITT Baltic project (2016-2019), with WWF Germany as one of the initialising partners, led to recommendations on the political implementation of ALDFG mitigation measures in the Baltic Sea ecoregion (Tschernij et al., 2019, https://marelittbaltic.eu/documentation). Methodology testing results of search, retrieval, processing and recycling options are incorporated in the pilot project reported here and considered for future longterm implementation in Germany. Clean Nordic Oceans (CNO) is a network of all Scandinavian countries with the aim to reduce the impact of fisheries and other marine litter on the Nordic seas (http://cnogear.org/about). During CNO projects, the retrieval experiences of Scandinavian countries together with fisherfolk and waste management options were investigated. One particularly successful initiative is the dismantling of fishing gear for recycing pathways in the Fisheries Association Norden (https://www.ffnorden.se), where end-of-life netting and lobster pots are separated into individual polymer and metal types and shipped to recyclers. Recycling is only available for pre-cleaned and sorted materials and not an option for most ALDFG (https://plastixglobal.com, https://nofir.no), but the effort of this Swedish fishing community demonstrates the best-practice feasibility of dealing with fishing gear and awareness raising. The Danish fisheries research institute DTU Aqua has recently conducted a sonar, diver and underwater video survey of lost fishing gear in conflict areas (Pedersen et al., 2021). An overabundance of ALDFG in areas with trawl and gillnet gear conflict could not be confirmed for Danish fishing zones, and only two ghost nets were identified. In Nothern Europe, Norway is the only country carrying out regular retrieval operations of ALDFG in North Sea fjords since more than three decades. In Norwegian deep fjord fisheries, lobster pots are costly and from the beginning, fisherfolk have reported lost pots because of their high economic value and the benefit of keeping fishing grounds clean. The implementation in Norway through the Fisheries Directorat serves as a template for longterm implementation of lost gear retrievals in collaboration with the fishing sector (https://www.fiskeridir.no/English/Fisheries/Marine-litter/Retrieval-of-lost-fishing-gear). The key to success is the reporting of loss positions by fishers, which requires that fishers are not discouraged by possible economic consequences of reporting of their own and other fishers lost gear encountered at sea. With the first state-funded project in Mecklenburg-Western Pomerania, fishers are reimbursed for search and retrieval activities for the first time in Germany, encouraging reporting and allowing mitigation of the impact of both historic and contemporary ALDFG and a healthier Baltic Sea seafloor ecosystem.

Outlook and summary

Pilot projects by German coastal states

The European Marine Strategy Framework Directive requires Member States to establish good environmental status in the European Seas (MSFD 2008/56/EC, https://www.msfd.eu). Since 2021, the environmental ministry of Mecklenburg-

Western Pomerania supports the retrieval of ALDFG by WWF in cooperation with fishing vessels. A similar project is planned from 2023 onwards in Schleswig-Holstein. ALDFG has accumulated in the Baltic Sea since the introduction of plastic nylon netting in the 1960s (Predki et al., 2011; Tschernij et al., 2019, see also https://britishseafishing.co.uk/ghost-nets, Radhalekshmy and Nayar, 1973). Most of the trawl netting retrieved during the project is historical from pre-GPS losses, where accurate locations of wrecks and rocks were not available to trawlers. This is confirmed by the retrieving fishers and is evidenced in the mesh width in the case of trawl cod ends, which was narrower 30 years ago than is allowed today, and in fibre abrasion. Gillnets are still lost today during sport boat accidents, storms, and winter ice (see also Richardson et al., 2021 for causes of loss in other European fisheries). Fisheries benefit from clean fishing grounds, but retrievals are costly and the locations of lost nylon gear on the seafloor are unknown. The pilot projects encourage fisherfolk to participate in retrieval activities and reimburse labour, fuel, and harbour costs with the overarching aim to mitigate ALDFG impact. During the first project year, five small fishing enterprises were actively involved with their vessels in the project, either through sonar charting trips or through ALDFG retrieval activities at sea, or both.

Fisherfolk in Germany and throughout Europe are aware of plastic marine litter through passively fished waste supported by state authorities, including at the German Baltic Sea. The Fishing for Litter scheme (F4L), coordinated by NABU and now in its 11th year in Germany, receives wide participation in the fisheries communities. Originally coordinated through KIMO International in the Netherlands (https://fishingforlitter.org), eight countries and one ecoregion participate today. For F4L UK, it was shown that litter collection at sea increases awareness and best practice behaviour among fisherfolk (DEFRA, 2014; Wyles et al., 2019). However, passively fished gear segments tend to be small (Dau et al., 2014), and complete ALDFG is not captured in passively fished waste during regular fishing operations. In contrast, during this pilot project, extended gillnet segments of several hundred meters in length and trawl fragments exceeding one tonne of weight were retrieved by fishing vessels.

WWF Ghostdiver App

The internationalised WWF Ghostdiver App, with support from the Federal Ministry for the Environment through the European Environment Initiative EURENI (https://www.z-u-g.org/aufgaben/europaeische-umweltschutzinitiative), is available since August 2022. In contrast to other digital applications and databases, such as e.g., the recorder app and database for ghost gear of the Global Ghost Gear Initiative (https://www.ghostgear.org), of which WWF is a partner, the Ghostdiver App incorporates the sonar methodology. WWF's app allows recreational divers to participate in the verification of ALDFG suspect sonar positions generated during sonar area searches. In addition, "WWF Ghostdiver" encourages reporting of lost gear and warns divers against self-commissioned retrievals, as these 1) can be a dangerous health and life risk for divers when getting entangled, and 2) state authorities are held responsible for cleaning actions on the seafloor to improve the good environmental status according to the EU Marine Strategy Framework Directive. For the methodology development and the definition of implementation measures for lost gear retrievals, the German Federal Environment Agency has contributed to this effort. With the initiated and announced state projects, Mecklenburg-Western Pomerania and Schleswig-Holstein are accepting responsibility for lost fishing gear, including historic plastic wastes, in their coastal waters for the first time.

The internationalised version of this citizen diver approach can be adapted by NGOs worldwide. Precise, verified positions of ALDFG will enable dedicated retrieval operations coordinated by state or regional authorities. In collaboration with WWF Mediterranean, France and Italy, WWF Germany's methodology was tested in the heavily polluted Mediterranean Sea in late summer 2022 for the first time.

Summary of case study results

With a total of 24 tonnes of ALDFG retrieved near Rügen Island alone from the project initiation in 2014 until the end of 2021, and more than 30 recovered gillnet fragments, the combination of sonar searches, diver verification and retrievals with fishing vessels has turned out highly effective in reducing the impact of ALDFG in the German Baltic Sea. An ecologically viable waste management pathway needs to be established prior to retrieval actions to ensure that ALDFG does not contaminate landfills. Efficient removal fosters healthy seabed habitats and mitigates the long-term contamination of the marine food web with microplastic fibres and particles, from which divers, fisherfolk and seafood consumers benefit in addition to the marine ecosystem.

Data availability statement

The datasets presented in this article are not readily available because the sonar data employed in this article are proprietary to WWF Germany and not publicly available. Requests to access the datasets should be directed to andrea.stolte@wwf.de.

Author contributions

AS: lead project manager, coordination of sonar excursions, retrieval campaigns, waste management solutions, data analysis. GD: co-project manager, lead WWF Ghostdiver app development, coordination of diving activities, sonar and retrieval campaigns. JL: project initiator and project leader 2014-2020, political implementation and initiation of state pilot projects. ML: coordinator WWF Ghostdiver app and data management. MG: development of analysis script for sonar data positions and first data base. CF: sonar trainer and long-term sonar search for ALDFG expert with Northwest Straits Foundation. WF: sonar driver and chief sonar analyst, verification diver and support of retrieval campaigns. CH: sonar driver and scientific diver including sonar data analysis and gear retrieval campaigns. HV: head of WWF international marine centre, funding and overarching project support. SW: lead scientist German Federal Environment Agency on marine litter and ALDFG, expert harm of plastic litter in the marine environment, scientific verification diver.

Funding

WWF Germany is sincerely grateful for unabated support by PreZero Lizenz GmbH (formerly Karl Tönsmeier Entsorgungswirtschaft GmbH & Co. KG) throughout the project lifetime since 2015. Without this long-term stability of base funding, this pilot project would not have been possible. The sonar searches were supported by the German Federal Environment Agency, who also supported the pilot excursion into the North Sea, through a Ministry for the Environment non-governmental organisations grant (FKZ 373820145), as well as several German Postcode Lotterie project grants (FV-1619, FV-4067), both of which also supported some of the retrieval activities. GD, ML and AS acknowledge support by NUE/BINGO Lottery for the development of the Ghostdiver App prototype and by the Federal Ministry for the Environment through the European Environment Initiative EURENI for WWF Ghostdiver's final development and internationalisation (EURENI_21_D_020). The state pilot project in Mecklenburg-Western Pomerania is supported by the Ministry for Agriculture, Fisheries and the Environment of Mecklenburg-Western Pomerania through a State Promotion Institute grant (LFI-LM-FA-01-21). The authors are grateful to the German Edeka Corporation and all private donors for their ongoing support throughout this project. This study received funding from PreZeroLizenz GmbH, formerly Karl TönsmeierEntsorgungswirtschaft GmbH & Co., and the Edeka Corporation. The funders were not involved in the study design, collection, analysis, interpretation of data, the writing of this article or the decision to submit it for publication.

Acknowledgments

This project would not be possible without the support of a substantial number of diving and sonar teams and local fisherfolk.This work would not have been possible without the intensive contributions of Wolfgang Frank, our main sonar driver and interpreter-cum-diver, Christian Howe, Philipp Schubert, Florian Hubert, Uli Kunz and all connected divers of the scientific diving team submaris, professional divers Jochen Firzlaff and Olaf Döhler, Stefanie Werner of the Federal Environment Agency for her support in the verification diving teams and all matters around marine litter, and the TSCW Warnemünde, Uli Baumhör, Ingo Oppelt, and all recreational divers carrying out verification dives. We are sincerely grateful to all fisherfolk involved in the project, including Karl-Heinz Neumann and Günther Baltsch, the fisheries associations Freest and Greifswald-Wieck, Sebastian Erler and his crew on vessel "Crampas", Lars and Jörg Engels on trawler "Bergen", Martin Saager and Thomas Peters for the very first fishing vessel sonar trials, and all fishers that will be engaged in the state-funded projects in the near future for their motivation, participation and patience. Our sincere thanks to Hannah Siegesmund for her intensive data work that enabled the build-up of the first sonar data base. For support during recycling trials and finding solutions for waste management, we are grateful to Dr. Michael Krüger's and Falk Schneider's ongoing enthusiasm and contributions. We also sincerely wish to thank the referees for their intense effort and detailed comments provided, which substantially helped improve the manuscript.

Conflict of interest

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

Publisher's note

References

Bergmann, M., Lutz, B., Tekman, M. B., and Gutow, L. (2017). Citizen scientists reveal: Marine litter pollutes Arctic beaches and affects wild life. *Mar. pollut. Bull.* 1251–2, 535–540. doi: 10.1016/j.marpolbul.2017.09.055

BMUB (Federal Ministry of the Environment, Nature Conservation, Construction and Nuclear Safety (2016) *MSFD programme of measures for marine protection in the German parts of the north Sea and the Baltic Sea*. Available at: http://www.meeresschutz.info/berichte-art13.html?file=files/meeresschutz/berichte/art13-massnahmen/MSFD_Art13_Programme_of_Measures_English-Summary.pdf.

British Sea Fishing. Available at: https://britishseafishing.co.uk/ghost-nets (Accessed Aug 12th, 2022).

Brown, J., and Macfadyen, G. (2007). Ghost fishing in European waters: Impacts and management responses. *Mar. Policy* 31 (4), 488–504. doi: 10.1016/j.marpol.2006.10.007

Clean Nordic ocean. Available at: http://cnogear.org/about (Accessed Aug 10th, 2022).

Dau, K., Millat, G., Brandt, T., and Möllmann, N. (2014) Pilotprojekt fishing for litter in Niedersachsen. *Final report 2013 – 2014*. Available at: https://muell-im-meer.de/sites/default/files/2020-08/Fishing%20for%20Litter%20in%20NI_2013-2014-web.pdf.

DEFRA (2014) *Evaluation of the fishing for litter scheme*. Available at: http://sciencesearch.defra.gov.uk/Default.aspx?Menu=Menu&Module=More&Location=None&Completed=0&ProjectID=17938.

Dive against debris – PADI training programme. Available at: https://www.diveagainstdebris.org (Accessed Aug 12th, 2022).

European Environment initiative EURENI. Available at: https://www.z-u-g.org/aufgaben/europaeische-umweltschutzinitiative (Accessed Aug 11th, 2022).

Fenn Enterprises Sonar Search & ALDFG removals (2022). Available at: https://fennenterprises.com/projects (Accessed June 21st, 2022).

Fisheries Association Norden, Smögen Municipality, Sweden. Available at: https://www.ffnorden.se (Accessed Aug 10th, 2022).

Fisheries history & high-seas trawler statistics in Eastern Germany. Available at: http://www.rostocker-hochseefischerei.de/schiffe/schiffe.php (Accessed Aug 10th, 2022).

Fossi, M. C., Baini, M., Panti, C., Galli, M., Jiménez, B., Muñoz-Arnan, J., et al. (2014). Are whale sharks exposed to persistent organic pollutants and plastic pollution in the gulf of California (Mexico)? First ecotoxicological investigation using skin biopsies. *Comp. Biochem. Physiol. C Toxicol. Pharmacol.* 199, 48–58. doi: 10.1016/j.cbpc.2017.03.002

Fossi, M. C., Coppola, D., Baini, M., Galli, M., Jiménez, B., Muñoz-Arnan, J., et al. (2014a). Large Filter feeding marine organisms as indicators of microplastic in the pelagic environment: the case studies of the Mediterranean basking shark (Cetorhinus maximus) and fin whale (Balaenoptera physalus). *Mar. Environ. Res.* 100, 17–24. doi: 10.1016/j.marenvres.2014.02.002

Fossi, M. C., Panti, C., Baini, M., and Lavers, J. L. (2018). A review of plastic-associated pressures: Cetaceans of the Mediterranean Sea and Eastern Australian shearwaters as case studies. *Front. Mar. Sci.* 5. doi: 10.3389/fmars.2018.00173

Fossi, M. C., Panti, C., Guerranti, C., Coppola, D., Giannetti, M., Marsili, L., et al (2012). Are baleen whales exposed to the threat of microplastics? A case study of the Mediterranean fin whale (Balaenoptera physalus). *Mar. pollut. Bull.* 64 (11), 2374–2379. doi: 10.1016/j.marpolbul.2012.08.013

Galgani, F., Hanke, G., and Maes, T. (2015). "Global distribution, composition and abundance of marine litter," in *Marine anthropogenic litter*. Eds. M. Bergmann, L. Gutow and M. Klages (Cham, Switzerland: Springer). doi: 10.1007/978-3-319-16510-3_2

GESAMP (2021). "Sea-based sources of marine litter," in *(IMO/FAO/UNESCO-IOC/UNIDO/WMO/IAEA/UN/UNEP/UNDP/ISA joint group of experts on the scientific aspects of marine environmental protection)*. Ed. K. Gilardi. London: International Maritime Organization (IMO). Available at: http://www.gesamp.org/publications/sea-based-sources-of-marine-litter

Ghostdiving – organisation of recreational divers retrieving ghost gear. Available at: https://www.ghostdiving.org (Accessed Aug 10th, 2022).

Gilman, E., Musyl, M., Suuronen, P., Chaloupka, M., Gorgin, S., Wilson, J., et al. (2021). Highest risk abandoned, lost and discarded fishing gear. *Sci. Rep.* 11, 7195. doi: 10.1038/s41598-021-86123-3

Global Ghost Gear Initiative (GGGI). Available at: https://www.ghostgear.org (Accessed Aug 10th, 2022).

Global Ghost Gear Initiative (GGGI) (2021) *Best practice framework for the management of fishing gear*. Available at: https://www.ghostgear.org/news/2021/6/25/best-practice-framework-refresh.

HELCOM pressure group on marine litter. Available at: https://helcom.fi/action-areas/marine-litter-and-noise/marine-litter (Accessed Aug 10th, 2022).

Helsinki Commission (HELCOM) *Baltic Marine environment protection commission*. Available at: https://helcom.fi (Accessed Aug 10th, 2022).

Jacobsen, J. K., Massey, L., and Gulland, F. (2010). Fatal ingestion of floating net debris by two sperm whales (Physeter macrocephalus). *Mar. pollut. Bull.* 60, 765–767. doi: 10.1016/j.marpolbul.2010.03.008

Kim, D., Kwon, B.-O., and Choi, K. (2020). Impact of derelict fishing gear on the seafloor integrity and benthic communities in the macrotidal flats from northern gyeonggi bay, west coast of Korea. *Sci. Total Environ.* 745, 141168. doi: 10.1016/j.scitotenv.2020.141168

KIMO *International fishing for litter scheme*. Available at: https://fishingforlitter.org/ (Accessed Aug 9th, 2022).

Koelmans, A. A., Kooi, M. L., Kara, L., and van Sebille, E. (2017). All is not lost: deriving a top-down mass budget of plastic at sea. *Environ. Res. Lett.* 12, 114028. doi: 10.1088/1748-9326/aa9500

Kühn, S., and van Franeker, J. A. (2020). Quantitative overview of marine debris ingested by marine megafauna. *Mar. pollut. Bull.* 151, 110858. doi: 10.1016/j.marpolbul.2019.110858

Lebreton, L., Slat, B., Ferrari, F., Sainte-Rose, B., Atiken, J., Marthouse, R., et al. (2018). Evidence that the great pacific garbage patch is rapidly accumulating plastic. *Sci. Rep.* 8, 4666. doi: 10.1038/s41598-018-22939-w

Löptien, U., and Dietze, H. (2022). Retracing cyanobacteria blooms in the Baltic Sea. *Sci. Rep.* 12, 10873. doi: 10.1038/s41598-022-14880-w

Macfadyen, G., Huntington, T., Cappell, R. UNEP/FAO, FAO FISHERIES AND AQUACULTURE TECHNICAL PAPER and UNEP REGIONAL SEAS REPORTS AND STUDIES (2009). *Abandoned, lost or otherwise discarded fishing gear*. FAO, Rome: UNEP.

MARELITT *Baltic Project reports*. Available at: https://marelittbaltic.eu/documentation (Accessed Aug 9th, 2022).

Marine strategy framework directive. Available at: https://www.msfd.eu (Accessed Aug 15th, 2022).

Meier Markus, H. E., Kniebusch, M., Dieterich, C., Gröger, M., Zorita, E., Elmgren, R., et al. (2022). Climate change in the Baltic Sea region: A summary. *Earth Syst. Dynam.* 13, 457–593. doi: 10.5194/esd-13-457-2022

Moschino, V., Riccato, F., Fiorin, R., Nesto, N., Picone, M., Boldrin, A., et al. (2019). Is derelict fishing gear impacting the biodiversity of the northern Adriatic Sea? an answer from unique biogenic reefs. *Sci. Total Environ.* 663, 387–399. doi: 10.1016/j.scitotenv.2019.01.363

Mouat, J., Lozano, L., Rebeca, B., Hannah, KIMO (2010) *Economic impacts of marine litter*. Available at: https://www.kimointernational.org/wp/wp-content/uploads/2017/09/KIMO_Economic-Impacts-of-Marine-Litter.pdf.

Newman, S., Watkins, E., Farmer, A., ten Brink, P., and Schweitzer, J.-P. (2015). "The economics of marine litter," in *Marine anthropogenic litter*. Eds. M. Bergmann, L. Gutow and M. Klages (Springer, Cham). doi: 10.1007/978-3-319-16510-3_14

NOFIR *Recycling of end-of-life fishing gear*. Available at: https://nofir.no (Accessed Aug 15th, 2022).

Northwest Straits Foundation. Available at: https://nwstraitsfoundation.org/ https://nwstraitsfoundation.org/derelict-gear (Accessed June 21st, 2022).

Norwegian Fisheries Directorat lost gear retrieval campaigns. Available at: https://www.fiskeridir.no/English/Fisheries/Marine-litter/Retrieval-of-lost-fishing-gear (Accessed Aug 10th, 2022).

OSPAR *Convention for the protection of the marine environment of the north-East Atlantic*. Available at: https://www.ospar.org/work-areas/eiha/marine-litter (Accessed Aug 10th, 2022).

Pedersen, E. M., Andersen, N. G., Egekvist, J., Nielsen, A., Olsen, J., Fletcher, T., et al. (2021). Ghost nets in Danish waters. DTU Aqua Report No.394-2021. *Natl. Institute Aquat. Resour*. Technical University of Denmark. 83 pp. Available at: https://orbit.dtu.dk/files/272867717/394_2021_Ghost_nets_in_Danish_waters.pdf

Pham, C. K., Ramirez-Llodra, E., Alt, C. H. S., Amaro, T., Bergmann, M., Canals, M., et al. (2014). Marine litter distribution and density in European seas, from the shelves to deep basins. *PloS One* 9 (4), e95839. doi: 10.1371/journal.pone.0095839

Plastix Global *Recycling of end-of-life fishing gear and other litter*. Available at: https://plastixglobal.com (Accessed Aug 15th, 2022).

Prędki, P., Kalinowska, M., Migdał, S. WWF Poland (2019) *MARELITT Baltic report 1: Derelict fishing gear mapping and retrieval methodologies*. Available at: https://www.marelittbaltic.eu/documentation.

Predki, P., Kasperek, Stanisław, Hac, B., Stanuch, K., Szulc, M. WWF Poland (2011) *Ecological effects on ghost net retrieval in the Baltic sea. BalticSea2020, pilot project: Collecting ghost nets final project report*. Available at: https://www.balticsea2020.org/english/alla-projekt/rovfisken/fishery-completed-projects/214-collecting-ghost-nets-in-the-baltic-sea

Radhalekshmy, K., and Gopalan Nayar, S. (1973). Synthetic fibres for fishing gear. fishery technology. *Fish. Institute India*. 142–165. Available at: https://aquadocs.org/mapping/18232/1/FT10.2_142.pdf

Richardson, K., Hardesty, B. D., Vince, J. Z., and Wilcox, C. (2021). Global causes, drivers, and prevention measures for lost fishing gear. *Front. Mar. Sci.* 8. doi: 10.3389/fmars.2021.690447

Sahlin, J., and Tjensvoll, I. (2018) *Environmental impact assessment: Retrieval of derelict fishing gear from the Baltic sea. MARELITT Baltic project report no. 9*. Available at: https://www.marelittbaltic.eu/documentation.

Sherrington, C., Darrah, C., Hann, S., Cole, G., and Corbin, M. (2016) *Study to support the development of measures to combat a range of marine litter sources. report for the European commission DG environment*. Available at: https://www.eunomia.co.uk/reports-tools/study-to-support-the-development-of-measures-to-combat-a-range-of-marine-litter-sources.

Stolte, A., and Schneider, F. (2018) *Recycling options for derelict fishing gear. MARELITT Baltic project report no. 5*. Available at: https://www.marelittbaltic.eu/documentation.

Thompson, R. C., Olsen, Y., Mitchell, R. P., Davis, A., Rowland, S. J., Steven, J., et al. (2004). Lost at Sea: Where is all the plastic? *Sci. 304 Issue* 5672, 838. doi: 10.1126/science.1094559

Tschernij, V., Press, M., Migdal, S., Stolte, A., and Lamp, J. (2019). *The Baltic Sea blueprint, final report of the MARELITT Baltic EU INTERREG project*. Available at: https://marelittbaltic.eu/documentation.

Vanninen, P., Östin, A., Bełdowski, J., Pedersen, E. A., Söderström, M., Szubska, M., et al. (2020). Exposure status of sea-dumped chemical warfare agents in the Baltic Sea. *Mar. Environ. Res.* 161, 105112. doi: 10.1016/j.marenvres.2020.105112

Werner, S., Budziak, A., van Franeker, J. A., Galgani, F., Hanke, G., Maes, T., et al. (2016). *Harm caused by marine litter; European commission, joint research centre, marine strategie framework directive working group on marine litter - thematic report*. Available at: https://data.europa.eu/doi/10.2788/690366.

Weston, J. N.J., Carrillo-Barragan, P., Linley, T. D., Reid, W. D.K., and Jamieson, A. J. (2020). New species of eurythenes from hadal depths of the Mariana trench, pacific ocean (Crustacea: Amphipoda). *Zootaxa* 4748, 1. doi: 10.11646/zootaxa.4748.1.9

Wyles, K. J., Pahl, S., Carroll, L., and Thompson, R. C. (2019). An evaluation of the fishing for litter (FFL) scheme in the UK in terms of attitudes, behavior, barriers and opportunities. *Mar. pollut. Bull.* 144, 48–60. doi: 10.1016/j.marpolbul.2019.04.035