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Plastic pollution pathways from marine aquaculture practices and potential solutions for the North-East Atlantic region

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ABSTRACT

Aquaculture practices at sea are far from impact neutral and remain an important source of marine plastic pollution. With projected rapid continual growth in the sector, if left unmanaged, aquaculture pollution can have detrimental environmental and social implications. Using the DPSIR framework, the paper examines current practices and pathways of plastic pollution from marine aquaculture in the NE-Atlantic, drawing on findings from literature, stakeholder consultations and beach litter assessments. Pathways for aquaculture-related litter identified include rough weather, farmer behavior, inadequate access to recycling facilities, low price of consumable plastics and high cost of recycling. Beach litter analyses conducted as part of the study exposed serious issues of under quantification, resulting from difficulties in source identification and a lack of detailed categorization in official monitoring systems. The paper makes recommendations to improve litter quantification and waste management, including the use of local knowledge and experts to identify sources of marine litter.

1. Introduction

Marine plastic pollution is on the increase on a global scale. Every year, more plastics enter the seas and oceans and accumulate in the marine environment (Lavender Law et al., 2010; Jambeck et al., 2015). Aquaculture practices at sea are far from being impact neutral and remain a source of plastic pollution. Plastic debris originating from marine aquaculture can strangle and kill marine life, break down into microplastics, negatively impact recreational and cultural experiences and become ingested by marine organisms, of which many may be commercially targeted species intended for human consumption (Jacobsen et al., 2010; Van Cauwenberghe and Janssen, 2014; Rochman et al., 2015; Devriese et al., 2015; Kühn et al., 2015; Wyles et al., 2016).

Over the 10 years to 2019, global marine and coastal aquaculture production grew by 64% in volume, compared to only 4% growth for wild-capture fisheries production over the same period (FAO, 2021). As consumption increases with population growth and higher protein intake, production from marine aquaculture is projected to grow further still – to more than double by 2050 (DNV, 2021). Therefore, pollution, including plastic debris, from aquaculture practices is also expected to increase.

Plastics are widely used in current aquaculture practices, in a variety of forms with varying intended durations of use, depending on the aquaculture application. Examples include ropes, buoys and plastic mesh in shellfish farming; polystyrene cages, plastic ropes/cords and PVC pipes in finfish mariculture; and packaging materials for supplies of feed and chemicals used in fish on-growing as well as the presentation of final product and throughout their distribution chains (Huntington, 2019; Sandra et al., 2020). The wide applications of plastic use in aquaculture provide a great number of opportunities for waste or loss, and the problem is amplified by the inadequate waste management in the sector as result of poor staff awareness and the lack of waste collection facilities at harbors (Huntington, 2019; De Raedemaecker et al., 2020; GGGI, 2021).

While plastic pollution from aquaculture activities is not a novel problem in itself, research (refer to Fig. 1) and industry initiatives to address the issue have only picked up in the past two decades.

The purpose of this paper is to identify the key challenges and barriers to reducing macro-plastic littering from aquaculture practices in marine and coastal areas, and identify potential solutions to marine plastic pollution for the sector. The main research topic of this paper is mapping pathways of macro-plastic debris arising from aquaculture

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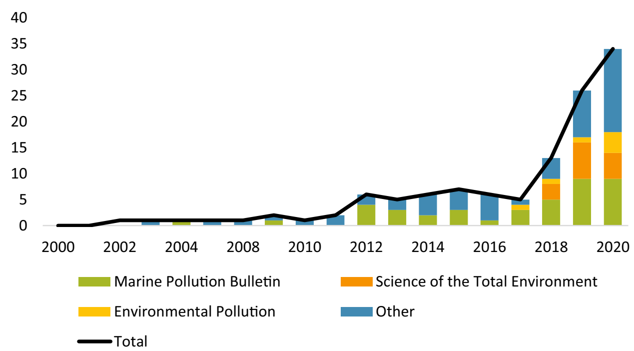

Fig. 1. Number of published articles on plastic pollution from aquaculture by source, from 2000 to 2020 (Scopus abstract and citation database, 2021).

activities in the North-East (NE) Atlantic region. Pathways are defined as the physical and/or technical means by which litter enters the marine environment (Veiga et al., 2017).

This research topic can be broken down into the following focus questions:

1. What is the extent of plastic pollution from aquaculture at sea in the NE-Atlantic region?
2. What are the main causes of plastic pollution from aquaculture activities in the NE-Atlantic?
3. What are the key challenges faced by the aquaculture sector in NE-Atlantic in reducing plastic use and pollution?
4. What steps could be taken to help aquaculture practices in the NE-Atlantic to become more impact neutral?

While micro-plastic pollution from aquaculture activities is also a great concern, direct source identification based on visual analysis is hampered by its physical dimensions as well as knowledge gaps on entry rates and distribution of micro-plastics entering the aquatic environment, and the specific contribution from fisheries and aquaculture sectors (Lusher et al., 2017; Huntington, 2019). As such the micro-plastic litter issue is not explored in this study.

2. Methodology

2.1. Literature review

A literature review was carried out to provide data on the extent of plastic pollution from marine and coastal aquaculture practices. The most extensive study conducted to date on debris originating from aquaculture activities across the European continent is the EASME-EMFF funded AQUA-LIT project (Sandra et al., 2020). The authors used data from various sources including OSPAR, HELCOM, EMODnet Chemistry and Marine LitterWatch, as well as scientific literature in the period from 2009 to 2019. Using these datasets, the share of aquaculture-related beach litter were calculated for the North Sea, Baltic Sea and Mediterranean Sea (Sandra et al., 2020). The exact share of aquaculture-related litter for the NE-Atlantic region calculated in this paper were made by consulting the AQUA-LIT, OSPAR Beach Litter[1] and Marine Litter Watch[2] databases using data from 2009 to 2019. The OSPAR Beach Litter Guideline (OSPAR, 2010) includes four litter categories that can be specifically linked to the aquaculture sector: No. 114 'lobster and fish tags', No. 28 'oyster nets or mussel bags including plastic stoppers', No. 29 'Oyster trays (round from oyster cultures)' and No. 30 'plastic sheeting from mussel culture (Tahitians)' (Sandra et al., 2020). The Marine LitterWatch database also includes four similar litter categories that can be linked to the aquaculture sector (Sandra et al., 2020): G43 'Tags (Fisheries and industry)', G45 'Mussels nets, Oyster nets', G46 'Oyster trays (round from oyster cultures)' and G47 'Plastic sheeting from mussel culture (Tahitians)'.

Another detailed account for sources of aquaculture pollution is the White Paper by Aquaculture Stewardship Council (ASC), which was formulated to guide the ASC certification review process (Huntington, 2019). In addition to these two core pieces of literature, a systematic review of scientific articles was conducted through a Scopus search over the five-year period from 2015 to 2019. This was done using the search terms "aquaculture" AND "plastic" AND "pollution" OR "litter", which yielded 57 results. Of these, 27 articles focusing on micro-plastics were excluded and a final selection of nine deemed relevant to the research topics of this study were assessed (Fig. 1).

2.2. Case studies: in-depth beach litter surveys

To illustrate the added value of in-depth beach litter analyses in gaining a better understanding on the sources, origin and pathways of marine litter, including those from aquaculture activities, two in-depth beach litter analyses were conducted. For this purpose, in October and December 2019, beach litter was collected from the (uninhabited) island of Griend in the Wadden Sea in the Netherlands (Strietman et al., 2020), and a secluded beach close to Old Dorney Harbour in North-Western Scotland. The choice of the two beach locations was made to ensure minimum interference from organized and unorganized community clean-ups, and in turn, provide an accurate representation of the local beach litter situation. The location of the Scottish beach was also in relative proximity to where aquaculture activities take place.

In both instances, the Litter-ID method was used to analyze the beach litter post collection (Strietman et al., 2021). This method has been developed as an extension to the OSPAR Beach Litter Monitoring Guideline (OSPAR, 2010). The purpose is to obtain a greater detailed characterization of the composition, source and pathway of beach litter in order to give an accurate assessment of its interaction with the local ecosystem.

As part of the analysis procedure, each item is first sorted into one of the 112 OSPAR beach litter categories. Applying the Litter-ID protocol, items for several OSPAR categories are then further sorted into additional subcategories based on the type and origin of the item, For each category and subcategory, numbers and weight are recorded along with (where possible) its source and origin based on external characteristics, such as label texts and/or other recognizable indications. After sorting into their respective (sub)categories, all items are then photographed for later reference. In the case of Griend, stakeholders – including a fishing industry expert, volunteers involved in local beach clean-ups, government officials and NGO representatives – were engaged in the beach litter analysis in order to provide additional expert-judgment into the origin and source of items, specifically those stemming from local activities. In the case of Old Dorney Harbour, the analysis results were verified with aquaculture stakeholders interviewed in North-Western Scotland.

Since the Litter-ID protocol allows for further characterization and source identification of litter using additional subcategories within the OSPAR framework, more items can be explicitly linked to the aquaculture sector (e.g. pipes used in salmon cages which falls under 'other plastic/polystyrene items', which is not a category specific to aquaculture under OSPAR) than only the four specific litter categories that are available for the sector under the OSPAR framework.

[1] The OSPAR Beach Litter Database is available online at https://beachlitter.ospar.org/.

[2] The Marine LitterWatch database is available by the European Environment Agency at https://www.eea.europa.eu/themes/water/europes-seas-and-coasts/assessments/marine-litterwatch/.

2.3. Stakeholder consultation

Stakeholders from the aquaculture industry were consulted via 1) visits in December 2019 to three aquaculture companies in Scotland covering activities stemming from five farming locations as well as 2) a stakeholder workshop and face-to-face interviews, conducted as part of the AQUA-LIT project (De Raedemaecker et al., 2020). The AQUA-LIT stakeholder workshop was held in Ostend, Belgium in November 2019 and consisted of fifteen stakeholders from five different countries in the North Sea region – Belgium, France, the Netherlands, Norway and the UK. The face-to-face interviews also involved (another) fifteen interviewees from the same region, carried out over the period from August 2019 to February 2020, with three interviews held in person and twelve conducted over online calls. For the farm visits, key industry players in salmon, oyster and mussel culturing in North-Western Scotland were interviewed.

The objective of the farm visits was to establish the current pathways (i.e. pressures) of macro-plastic waste and pollution from aquaculture activities in the NE-Atlantic region, and the best practices undertaken by industry leaders at the time to prevent and mitigate plastic pollution or use. Possible solutions that could be achieved in the future were explored in context with technological advancements and government regulations necessary to overcome existing barriers. Similar issues were also discussed during stakeholder engagements carried out as part of the AQUA-LIT project, focusing in particular on the North Sea region. The AQUA-LIT face-to-face interviews and North Sea Learning Lab workshop were centered around developing a toolbox of solutions to prevent, reduce, monitor, remove and recycle plastic waste in aquaculture practices based on stakeholders' perspectives (De Raedemaecker et al., 2020). The fifteen targeted stakeholders interviewed covered all stages of the life cycle of fish and shellfish aquaculture farming, including two aquaculture farmers, two equipment manufacturers, six academic researchers, one NGO representative, one government official, and three other participants (e.g. consultants, students etc.). At the Learning Lab workshop, knowledge sharing and co-creation was encouraged through breakout sessions at round tables, around three discussion points on tackling of marine litter: prevention and reduction, monitoring and quantification, and removal and recycling (Fig. 2).

2.4. The DPSIR framework

The DPSIR framework is a systems-based approach in analyzing the relationships between human activities and the environment, in particular pressures created by human demands (Atkins et al., 2011). This widely used framework provides a holistic overview of the causes, consequences and possible responses to the problem (EEA, 1997; Kristensen, 2004; Maxim et al., 2009; Patrício et al., 2016; Rijksoverheid, 2018).

Fig. 2. Aquaculture litter from shellfish farming (e.g. seed collectors, mussel socks, Tahitians and cones, taquets/pins, buoys etc.), AQUA-LIT stakeholder workshop in Ostend, Belgium. Photo: M. Skirtun.

In the context of macro-plastic pollution from aquaculture practices, this framework is used to bring together information from different sources in a systemic manner. The outcomes of the workshop, interviews and data analyses are structured in the DPSIR framework. More specifically, the data collected from beach litter analyses and literature review are employed to paint a picture for the broader context of marine litter from aquaculture (e.g. drivers, state and impact), while the discussions from the workshop and industry consultations provide a more holistic examination of the challenges faced and possible solutions (e.g. pressures, responses).

3. Results

3.1. Drivers for aquaculture-related litter in the marine environment

The role of aquaculture in feeding a growing population is more important than ever – both in terms of food security and employment opportunities (Richens, 2020). The sustained consumption of aquaculture products over the last decade has supported the growth in aquaculture production within the 28 Member States of the European Union (EU), which reached a 10-year high of 1.37 million tons with a value of EUR 5.06 billion in 2017 – representing a doubling in value and a 11% growth in volume compared to a decade ago (EUMOFA, 2019). Marine aquaculture production from continental Europe (including non-EU Member States) reached 2.58 million tons in 2018, of which 73% or 1.89 million tons came from finfish mariculture (FAO, 2020b). In the NE-Atlantic OSPAR region, production volume have increased from 1.5 million tons to around 2.2 million tons between 2008 and 2018, with Norway being by far the largest producer (FAO, 2021).

Projected increase in global seafood demand and a stable wild-capture production are key drivers for growth in aquaculture production (DNV, 2021). The latter is in part a result of a reduction in underfished fish stocks, with majority of the world fish stocks fished at maximum sustainable yield or depleted/overfished as of 2017 (FAO, 2020b). Lower costs due to accumulated experience and greater technology uptake, are also expected to drive aquaculture production in the future (DNV, 2021). With rapid growth in sector – past, present and future – litter from aquaculture activities is expected to remain an important source of plastic pollution in the marine environment. Rough weather and inadequate waste management in the sector, as result of poor staff awareness and the lack of access to waste collection facilities, further exacerbate the situation (Huntington, 2019; De Raedemaecker et al., 2020).

3.2. Pressures from aquaculture activities on litter in the marine environment

To identify pressure hotspots of plastics pollution from aquaculture, an overview of common plastic use in current aquaculture practices is presented in Table 1. In addition to those listed in Table 1, there are also various other consumer products used by staff working at aquaculture facilities and throughout the distribution chain that are made from plastic, such as rubber gloves and protective clothing, fish transport trays and packaging, as well as packaging of food and beverages consumed by the crew working on land and offshore (pers. comm. through interviews 2019, Sandra et al., 2020).

Based on the common uses of plastics in aquaculture in the NE-Atlantic region outlined, a number of pathways for plastic pollution to enter the marine environment were then identified during the industry visits and stakeholder workshop (see Table 2 for summary). For example, rough weather conditions can cause damage to equipment on

Table 1
Marine aquaculture species with the highest production in the NE-Atlantic and the types of plastics used in their associated farming practices (updated from: EC, 2012, STECF, 2018, Huntington, 2019, Sandra et al., 2020, FAO, 2020a).

Key species	Key farming countries	Farming techniques	Types of plastics used
Salmon	Norway, the UK, Ireland, Denmark, France and Spain	From incubation tanks to fresh water tanks, to finally floating cages at sea	Floating collars (incl. handrails), net enclosures (incl. predator nets), buoys, ropes/cords, feeding pipes and hoppers, plastic sacs used in feed packaging etc.
Mussels	Spain, France, The Netherlands, The UK, Ireland, Germany, Norway, Denmark, Sweden and Portugal	i) Ropes or longlines suspended from fixed or floating rafts – Spain, Mediterranean, the UK and Ireland ii) Wooden stakes wrapped with collecting rope and covered with net – France iii) Plots – the Netherlands, the UK and Ireland	Buoys, ropes/cords, plastic strapping materials, mussel socks and cones/Tahitians, taquets or pins, raft floating, beacons and plastic bags (and mesh or other materials used to label beacons)
Oysters	France, Portugal, The UK, Ireland, Denmark, Norway, Spain and the Netherlands	i) off-bottom culture using plastic mesh bags – France ii) Suspended culture using ropes – Spain iii) bottom culture – less widespread today iv) deep water culture, placing oysters in parks and dredged	Collectors = coupelle or other seed collectors, polyester ropes/cords, ribbed plastic discs Culture = plastic mesh, tray/container or cage, and polystyrene buoys or other plastic floating devices
Clams	Portugal, Spain, Ireland and France	Reared in nurseries or farmed in meshed containers over culture tables. In Italy, Japanese clams are mostly pre-grown on wooden frames covered by plastic netting below water	Mesh bags, depuration trays and containers, buoys or other floating device, plastic netting

site (e.g. salmon feed pipes, nets etc.) as well as generate losses of items on board vessels visiting offshore aquaculture sites (e.g. gloves, food packaging, empty water bottles, loose ropes/cords etc.). Aquaculture farmers often have inadequate access to recycling facilities: this applies to both the availability of recycling companies in rural or remote areas, as well as readily accessible recycling points for staff working on sites (e.g. recycling bins on board vessels or at aquaculture site). For remote sites, it can be impossible or not feasible – economically, financially and/or time-effectively – to recover and recycle all waste materials (GGGI, 2021).

Plastic 'consumables' are inexpensive, single-use items that do not provide farmers the same level of incentive to avoid losing compared to more expensive and durable items (De Raedemaecker et al., 2020). For example, buoys can cost in excess of €100 each, so losses are more likely to be accidental because they are costly to replace (pers. comm. with Belgian mussel farmers 2019). The cost for gloves or Tahitians are only a few euros and designed for a limited number of uses, so there is not as much care taken to avoid losing such items. Most solutions to reduce plastic pollution discussed at the Learning Lab workshop were recognized to be too expensive to implement in practice at the present time, such as GPS satellite tracking on buoys and other equipment, and recovering/collecting *all* litter lost during storms or fallen over board

Table 2
Pathways for plastic pollution from aquaculture, identified based on stakeholder participatory processes.

Item	Pathway
PVC pipes (predominantly feed pipes) often used in offshore cage farms	Can be weakened when different sized feed pellets get stuck, and break around connectors, especially during rough weather events
Ropes/cords used to secure offshore cages	When frayed require trimming and taping of the ends to prevent future frays. This common practice can lead to offcuts ending in the sea if not secured or disposed of immediately
Tahitians and cones used in off-bottom mussel culture to prevent predatory species from eating the mussels (predominantly in northern France):	Can wear and break away with currents and storms
Floats and markers for beacons used in bottom culture for mussels (predominantly in the Netherlands)	Often involve strapping highly visible items such as bucket lids, potato/onion sacks and number plates onto beacons using inner tubes of tires or strapping bands. Similar to Tahitians and cones, these items and strapping materials can weather away with strong currents or storms
Mussel socks and pins used in off-bottom culture practices where mussel seeds are secured onto pilings with mussels socks, as well as taquets or pins which are used to prevent mussels from collapsing or coming off pilings before harvest time	Are vulnerable to strong weather elements
Oyster seed collectors or coupelle collectors used on tidal flats to catch oyster spats in the intertidal zone, as well as oyster trays/bags and plastic mesh used in on-growing	Can breakdown and wash away with strong currents and rough weather events
Buoys used in shellfish aquaculture and offshore cage farming	Can break away during strong storms and wash up on nearby beaches
Packaging from food or beverage consumed by crew, especially aboard vessels servicing offshore cages	Are sometimes intentionally discarded or accidentally lost during bad weather conditions
Other equipment and gear used whether on vessels servicing offshore cages or intertidal farming (e.g. rubber gloves, fish trays, lobster tags etc.)	Are sometimes intentionally discarded or accidentally lost during bad weather conditions

(De Raedemaecker et al., 2020). Moreover, aquaculture farmers in the UK and other parts of the NE-Atlantic region currently must pay to engage recycling companies to collect and take their plastic waste materials, and sometimes also to clean the plastic materials beforehand at their own costs – e.g. nets used in offshore cages must be cleaned before they can be accepted for recycling (pers. comm. with Scottish salmon farmers 2019).

Lack of understanding, awareness and education regarding the impacts of plastic pollution from aquaculture, as well as resistance to changing habits or attitudes, can also be a reason behind intentional littering or lack of care in minimizing littering at sea (Huntington, 2019, De Raedemaecker et al., 2020; GGGI, 2021). For example, when staff are securing ropes/cords on sea cages and cutting off frayed ends, it may be easier to throw into the water than to hold onto until they are back aboard the vessel (pers. comm. with Scottish salmon farmers 2019). Similarly, a lack of care taken in securing empty water bottles so that they are not easily blown over board can be due to individual attitudes or lack of company culture in promoting good recycling practice.

3.3. State of aquaculture-related litter in the marine environment

Across the NE-Atlantic, various marine and beach litter monitoring activities are conducted in the framework of the European Regional Sea Convention (i.e. OSPAR), the International Council for the exploration of the Sea (ICES) and the EU Marine Strategy Framework Directive (MSFD). The standardization of monitoring activities among OSPAR contracting parties and EU Member States allows for interpretation and comparison of the regional litter situation in the NE-Atlantic area and is key to understand current state of the plastic pollution problem (OSPAR, 2010).

As part of the AQUA-LIT project, the share of aquaculture-related litter as a portion of all beach litter recovered was calculated for the North Sea, Baltic Sea and Mediterranean Sea based on data collected from various sources including OSPAR, Marine LitterWatch, HELCOM and scientific literature over the period from 2009 to 2019 (Sandra et al., 2020). The figure for the North Sea region is estimated at 12.4%, and this includes various items commonly used in aquaculture but not unique to aquaculture (e.g. used both in fisheries and aquaculture). However, when the calculation is adjusted to focus only on the four item categories in the OSPAR Beach Litter Database specific to aquaculture, the figure drops to just 0.34%. When extended to the wider NE-Atlantic region, the share of aquaculture-related beach litter is reduced further to 0.32% when only using the four OSPAR item categories specific to aquaculture, and 0.13% when only using the four Marine LitterWatch aquaculture-specific item categories.

The geographic distribution of beach litter originating from shellfish culture in the North Sea region has been documented to centered mainly in the English Channel and Southern North Sea, while finfish farming litter has been recovered mostly from Northern North Sea, Skagerrak and Kattegat (Sandra et al., 2020). An interesting finding is that aquaculture-related litter found on Belgian, Dutch and German beaches have been primarily attributed from 'Bouchet' mussel and oyster cultivations, which are popular in Normandy, France (Fig. 2, Fig. 5, Sandra et al., 2020; Strietman et al., 2020). This result is significant because it reveals that, like litter from the fishing sector, plastic pollution from aquaculture is not confined to the location of farming activities and, along with other types of floating marine litter, may be transported to other areas under the influence of wind, waves and ocean currents (Van Sebille et al., 2020).

Investigations into aquaculture practices in Norway have found that an average of 25,000 tons of plastic from aquaculture is discarded at sea each year, specifically floating collars, plastic pipes, but also nets, feed hoses and ropes (Huntington, 2019). Using the rate of plastic waste discard from aquaculture production in Norway and applying it to the total production volume of the NE-Atlantic, this yields a result of more than 50,000 tons of plastic waste entering the marine environment (Huntington, 2019; FAO, 2021). This compares to an earlier calculation of plastic waste from aquaculture across the European Economic Area (EEA) – including all EU Member States, Norway and Iceland – by EUNOMIA (Sherrington et al., 2016), which places the estimated range between 3000 and 41,000 tons per annum, of which around 72% is likely to be plastic and 7% is deliberately discarded.

3.3.1. In-depth beach litter surveys using the Litter-ID protocol

As part of this study, two in-depth beach litter analyses were conducted with litter collected from beaches in North-Western Scotland (a beach near to Old Dorney Harbour) and in the Netherlands (on the island of Griend). The analyses were carried out using the Litter-ID protocol (Strietman et al., 2021), which extends upon the OSPAR Beach Litter Monitoring Guideline (OSPAR, 2010). As part of the protocol, additional subcategories were made for recognizable items that are not included in the OSPAR list of categories, including items that can be assigned to the aquaculture sector. Where, based on expert judgment by the research team and specialists consulted, the source could be determined by assessing external characteristics, markings or labels, litter items are assigned to their general source (fishery, aquaculture, shipping, industrial, household, or 'unknown'). The results are displayed Table 3 and Table 4.

Of the 1150 litter items collected near Old Dorney Harbour, 21 items (1.8%) could be traced directly back to aquaculture (Table 4). More specifically, 16 of which were plastic pipes, typically used in salmon cage farming, one mesh bag used in oyster farming and four lobster and fish tags (see Table 4 and Fig. 3). Under the OSPAR categorization only the mesh bag and the lobster and fish tags would have been assigned to categories specific to aquaculture, while the plastic pipes would have been registered under OSPAR ID 48 (Other plastic/polystyrene items), and would not have been assigned as such. This equates to a 0.43% (5 out of 1150) share, compared to 1.8% (21 out of 1150) when the Litter-ID method is applied.

In addition to the mesh bag and pipes, a number of rope off-cuts collected in Old Dorney Harbour were identified as potentially originating from aquaculture practices (e.g. used for securing cages or predator nets). The reason for this is that they featured taped-off ends and were of the typical length that matched the common practice of fortifying nets of offshore sea cages, as described during consultations with local salmon farming companies – i.e. taping rope ties prior cutting to avoid frays (see Fig. 4). However, as the source could not be assigned with 100% certainty, these items were not assigned to aquaculture for this analysis (instead, the source is registered as 'unknown' in Table 3).

For the beach litter analysis of Griend Island, 35 (0.9%) of the 3691 litter items could be traced directly back to aquaculture (Tables 3 and 4). These were mostly items used as beacons to identify mussel seed collection locations in the Wadden Sea, and are reused waste items such as bucket lids or number plates and onion bags (see Table 4 and Fig. 5). Farmers often choose the marker items for their size and visibility out at sea. Similar to the case with Old Dorney Harbour, most of these items would be formally registered under OSPAR ID 48 ('Other plastic/polystyrene items') in the OSPAR beach litter monitoring system, and as such would not be counted towards aquaculture-related litter. When using only the four OSPAR aquaculture-specific litter categories, shaded grey in Table 4, the share of beach litter from aquaculture reduces to just 0.27% (10 out of 3691). The large differences in calculated share of aquaculture-related litter for both the Griend and Old Dorney Harbour beach litter analyses tell a similar story to the estimates for the North Sea region, based on data used for the AQUA-LIT project.

3.4. Impact of aquaculture-related litter in the marine environment

The threat plastic pollution poses to the environment and wildlife is considered a global concern (Wilcox et al., 2015; Werner et al., 2016; Parker, 2019; GGGI, 2021). Nearly 700 species have been documented to be impacted by plastic pollution, with seabirds particularly vulnerable to plastic ingestion (Wilcox et al., 2015; Kühn et al., 2015; Parker, 2019). The key risks posed to wildlife from marine plastic pollution are identified by Werner et al. (2016) include: entrapment and entanglement of marine organisms; ingestion of plastic by animals; transfer of harmful chemicals (e.g. plastic additives) to wildlife; transport of non-indigenous species; and smothering of marine fauna.

Abandoned or lost fishing gear, also commonly used in aquaculture – e.g. netting for cages, ropes and line fragments – are often documented as a key source of marine wildlife entanglement (Butterworth et al., 2012; Werner et al., 2016; Parker, 2019). In the NE-Atlantic region, several publications have reported rather high rates of plastic ingestion by marine organisms (Murray and Cowie, 2011; Lusher et al., 2013; Foekema et al., 2013; Werner et al., 2016). A major concern related to ingestion is the transfer of chemical substances or plastic additives to individuals and its biomagnification up the food chain (e.g. Koelmans et al., 2016; Devriese et al., 2017; Boyle et al., 2020; GGGI, 2021).

Macro-plastic pollution in the form of lost or abandoned gear from aquaculture also pose more general threats to the marine environment and biodiversity through altering and/or modifying assemblages of species (Werner et al., 2016). This is primarily through the introduction of foreign species that are transported via floating plastic debris, or sunken litter that forms new artificial habitats, both of which threaten native biodiversity (Hinojosa and Thiel, 2009; Werner et al., 2016; GGGI, 2021). An example of how far aquaculture litter can travel is illustrated by the 'Bouchet' used in mussel and oyster cultivations in Normandy that are found along the Belgian, Dutch and German

Table 3
Beach litter analyses: Old Dorney Harbour, Scotland (December 2019) and island of Griend, the Netherlands (September 2019).

Source category	Fishery		Aquaculture		Shipping		Industrial		Household		Unknown		TOTAL	
Location[a]	ODH	Gnd	ODH	Grnd	ODH	Grnd	ODH	Grnd	ODH	Grnd	ODH	Grnd	ODH	Grnd
Number (#)	293	594	21	35	0	124	79	1305	223	1130	534	503	1150	3691
Share (%)	25.5%	16.2%	1.8%	0.9%	0%	3.4%	6.9%	35.4%	19.4%	30.6%	46.4%	13.6%	100%	100%

[a] ODH = Old Dorney Harbour and Grnd = the island of Griend.

Table 4
Beach litter analysis Griend Island, the Netherlands (collected September 2019) and Old Dorney Harbour (ODH), Scotland (collected December 2019): aquaculture-related items.

OSPAR ID	Category name	Subcategory	Total # (ODH)	Total # (Griend*)
6	Food containers incl. fast food containers	Onion bags		13
28	Oyster nets or mussel bags including plastic stoppers		1	8
29	Oyster trays (from oyster culturing)		0	0
30	Plastic sheeting from mussel culture (Tahitians)			2
48	Other plastic and polystyrene items	Black litter bags with cable ties		3
		Bucket lids		4
		Number plate		1
		Rubber bands		4
		Salmon farming plastic pipe	16	0
114	Lobster and fish tags		4	0
Total			21	35
Percentage of total			1.8%	0.9%

*Source: Strietman et al., 2020.
ODH = Old Dorney Harbour and Griend = the island of Griend. Cells shaded in grey refer to the four litter categories under OSPAR classification that are directly attributable to aquaculture.

Fig. 3. Oyster mesh bag and offshore cage pipes on beach near Old Dorney Harbour, Scotland. Photos: M. Skirtun.

Fig. 4. Rope off-cuts found on beach near Old Dorney Harbour, Scotland. Photos: W.J. Strietman.

Fig. 5. Aquaculture litter from mussel farming found on Griend Island, the Netherlands. Photos: M. Skirtun.

coastlines (Fig. 2, Fig. 5, De Raedemaecker et al., 2020; Strietman et al., 2020).

Moreover, depending on the type of plastic used, the breakdown process in the marine environment will vary. Expanded polystyrene used for insulation and fish boxes is extremely light and buoyant so it can accumulate on beaches but breaks easily into smaller pieces (Heo et al., 2013), while high-density polyethylene used for buoys, floats and storage tanks is tough and chemically resilient so it takes longer to fragment and abrade, but can weather and lead to microplastic formation (Huntington, 2019). Polyvinyl chloride (PVC) – the commonly used material in pipe and valve fittings for offshore cages, is extremely tough but rarely recycled – also takes time to fragment and abrade. Plastic materials used for the fabrication of ropes, cords and nets (e.g. nylon, polyethylene polypropylene, polyethylene terephthalate or polyester) vary in their strength and elasticity as well as the time to fragment and breakdown to microplastics (Huntington, 2019).

3.5. Response to aquaculture-related litter in the marine environment

There are currently a number of actions and initiatives taken by local governments, industry leaders and non-governmental organizations (NGOs), in the form of preventive and reactive measures to litter from aquaculture in the NE-Atlantic (e.g. Rijksoverheid, 2014; Cole et al., 2019; Gin et al., 2020). These include preventive actions in the form of government regulations around installations and materials used in aquaculture in order to meet certain technical standards of durability against environmental conditions faced by aquaculture farms (Hipólito et al., 2020). For example, Scotland has a Technical Standard for Finfish Aquaculture that specifies requirements for the design of equipment and gear used in offshore fish farming, including pens, cages, nets, feed barges, other installations and so forth (Marine Scotland, 2015). While not directly intended for the minimization of litter at sea, the standard does contribute positively to reducing equipment and gear loss in open waters.

At the industry level, current and possible future efforts to counter the generation of plastic waste from aquaculture (i.e. gear loss) – as well as ways to decommission, collect, recycle and reuse gear – were discussed during individual consultations with farms and at the AQUA-LIT workshop and interviews. The responses are in line with the best practices outlined by the Global Ghost Gear Initiative (GGGI, 2021) and they include:

- More adaptive gear to rough conditions offshore in the form flexible sea-proof installations. Examples include mussel farming longlines and anchors optimized to suit sea currents in the Belgian North Sea, and innovative offshore salmon cages that replace hamster wheels with predator poles or using only a single fish net and sinker ring (pers. comm. with Belgian mussel farmers and Scottish salmon companies 2019). The latter not only improve durability but also reduces the need for excess plastic use. In the Netherlands, a technical report that confirms storm resistance of aquaculture infrastructures is mandatory in receiving a permit, and this in turn, reduces the risk of gear loss (De Raedemaecker et al., 2020).
- Switching to equipment and gear made from natural or (marine) biodegradable materials as an alternative to plastics, such as biodegradable socks in off-bottom mussel culture, is being used by leading farms in both Scotland and the Netherlands (pers. comm. with Scottish and Dutch mussel farmers 2019). In the Shetlands, mussel pegs, which are often lost, have been replaced by continuous lines or loops (De Raedemaecker et al., 2020). There are also various pilot studies in other EU countries looking at the durability of biodegradable ropes (e.g. the BIOGEARS,[3] BLUENET[4] and DSOLVE[5] projects).
- Clean up and education programs or activities run by aquaculture farms with their staff and family members, and at times in partnership with NGOs or local communities, are important in building good company culture and changing operator attitudes/behavior towards plastic waste (pers. comm. with Scottish shellfish farmer 2019). There are several examples of this across the EU by small and major salmon and shellfish producers – i.e. Mowi Global Cleanup Day, Da Voar Redd Up, CERMAQ youth clean-up, etc. (De Raedemaecker et al., 2020). Clean up programs can also offer insights into the materials that are prone to be lost or in pollution hotspots. Companies who actively engage in annual clean ups and modifying their behavior and/or material use as a result, have also reported declines in plastic pollution over time (pers. comm. with Scottish shellfish farm 2019). In addition, awareness raising workshops, such as Pro Sea marine education,[6] for maritime professionals can be very beneficial in influencing behavioural changes (De Raedemaecker et al., 2020).
- Re-using, re-purposing and upcycling aquaculture gear is another response taken by industry leaders in terms of waste management. For example, some salmon farms in North-Western Scotland and the Shetlands are working closely with organizations and local agriculture farming communities to repurpose pipes and stanchions from offshore salmon farms in the construction of greenhouse,[7] tunnels or farm fences (pers. comm. with Scottish salmon farmers 2019). In the fisheries and aquaculture sector, there are companies and organizations who look for innovative ways to upcycle equipment waste, such as (nylon) nets and ropes, to produce sustainable consumer products like socks, bracelets, bags, swimwear, carpets and other textiles[8] (Mowi, 2020).
- Coordination of recycling programs is an initiative taken by some farms in more remote areas of Scotland, where supply of recycling services are limited. There are examples of shellfish aquaculture farms who coordinate efforts with local supermarkets, butchers and other businesses to combine items for recycling in order to make the services more accessible as recycling companies are often contracted from larger and more distant towns (pers. comm. with Scottish shellfish farm 2019). At the sector level, cooperation in collecting waste between several aquaculture companies is also present. SeaBOS[9] (Seafood Business for Ocean Stewardship) consist of 10 of the top world's largest seafood companies and has the aim to align their policies (incl. waste collection) to create a science-based global transformation towards sustainable seafood production and a healthy ocean. In this way, SeaBOS intends to introduce new standards for the entire supply chain.
- Improving company culture and increasing accessibility of recycling points within the corporation is an example of individual firm initiative that has been adopted by some offshore salmon farms. This includes making recycling bins more available on board support vessels and barges so that waste items collected from offshore farms can be immediately sorted without waiting to return to shore, reducing the need for plastic water bottles by providing re-usable water flasks and refillable water coolers, and actively fostering awareness around the workplace to recycle waste (pers. comm. with Scottish salmon farm 2019).
- Incorporating sustainability frameworks within company structure or industry associations is another example of individual firm initiative that can be taken. This includes having a core internal team or dedicated personnel within the company that focuses on sustainability and conduct internal audits, such as environmental assessments (pers. comm. with Scottish shellfish farm 2019). At the industry association or sector level, similar efforts can be taken through establishing forums that focus on sustainability issues such as pollution reduction/mitigation. Both examples can be found within the Scottish shellfish and salmon industries.
- Environmentally friendly packaging represents an avenue in reducing non− recyclable or biodegradable plastic use further down the value chain. Farms who are also distributors of their products have reported switching to more environmentally friendly packaging such as biodegradable mesh bags for clams, natural wooden trays for oysters, recyclable modified atmosphere packs (MAP) for vacuum sealed mussels and compostable cardboard fish boxes for salmon (pers. comm. with Scottish shellfish and salmon farms 2019). The Belgium division of Mowi, for example, has reported a reduction in plastic consumption by 96 tons per year by simply reducing the weight of MAP trays by 20% (De Raedemaecker et al., 2020).

Beyond the national and industry level, responses to plastic pollution from aquaculture are less prevalent. For example, there are currently no EU regulations on single-use plastics for aquaculture like that in place for household consumables,[10] nor preconditions for licensing including the quality standards of materials and the plastic waste management plans (Hipólito et al., 2020). Despite the Extended Producer Responsibility (EPR) schemes, certifications and decommissioning plans regarding circular design of gear and equipment are not in place yet (Hipólito et al., 2020). For the time being, EU funded projects (e.g. AQUA-LIT, BIOGEARS, BLUENET), national regulations and individual best practices (e.g. use of biodegradable materials in farming and packaging, marking and tracking of aquaculture gear, maintenance schemes for aquaculture infrastructures, feasible EPR schemes and shared responsibilities (Gin et al., 2020)) are leading the defense against

[3] Information on the BIOGEARS project can be found online at https://biogears.eu/.

[4] Information on the BLUENET project can be found online at https://www.bluenetproject.eu/.

[5] Information on the DSOLVE project can be found online at https://uit.no/research/dsolve-en.

[6] Information on the Pro Sea marine education program can be found online at https://www.prosea.info/.

[7] Information on the Polycrub community project can be found online at https://www.polycrub.co.uk/about.

[8] Information on the Healthy Seas initiative and products can be found online at https://www.healthyseas.org/products/.

[9] Information on the SeaBOS membership can be found online at https://seabos.org/.

[10] Information on regulations regarding single plastic use for household consumables in the EU can be found at: https://ec.europa.eu/environment/efe/news/european-parliament-votes-single-use-plastics-ban-2019-01-18_en.

plastic pollution from aquaculture. Similarly, ecolabel organizations have not introduced formal standards across the board to account for plastic waste from aquaculture farms, but ASC is in the process of correcting this (pers. comm. with ASC 2019).

4. Moving forward

Although marine plastic litter from aquaculture appears less significant compared to that from other sectors (e.g. fisheries, industrial etc.), it is important to bear in mind that the sector is still growing rapidly. Therefore, the problem should not be discounted as it will only continue to intensify with the expansion of the sector, and can potentially have detrimental environmental and social implications if left unchecked. This paper examines the problem of plastic pollution from aquaculture for the NE-Atlantic region using the DPSIR framework. However, insights and solutions gained from the region can be applied more broadly to the rest of the European continent. This is especially true for industries within the sector that use the same or similar farming technology – e.g. seabream and seabass farming in the Mediterranean employs offshore sea cages not unlike those found in the salmon aquaculture industry in the NE-Atlantic.

4.1. Monitoring and observation methods

Insight into the magnitude of plastic pollution from aquaculture is often hampered by the lack of appropriate observation and monitoring systems at the national or regional level. There are currently no requirements or standardized process for aquaculture farms to monitor gear loss. Most farms monitor their gear only after heavy storms rather than on a regular basis (De Raedemaecker et al., 2020). A standardization of monitoring approaches by industry bodies and/or governments will improve the quantification of gear loss, and prevent potential losses. Producers can be asked, for example, to report on-farm infrastructures and material use as part of licensing conditions, and the use of traceability measures (e.g. QR codes on individual equipment and gear) can help better identify and track origins of lost gear (De Raedemaecker et al., 2020).

The presence, composition, abundance and trends in marine litter, determined through sea(floor) monitoring campaigns and beach litter assessments, are in force in the NE-Atlantic region. The most commonly applied beach litter monitoring protocol is the OSPAR monitoring framework, which includes a list of 112 item categories to which beach litter can be assigned (OSPAR, 2010; OSPAR CEMP, 2020). Four of which can be directly attributed to the aquaculture sector: No. 114 ‘lobster and fish tags’, No. 28 ‘oyster nets or mussel bags including plastic stoppers’, No. 29 ‘Oyster trays (round from oyster cultures)’ and No. 30 ‘plastic sheeting from mussel culture (Tahitians)’. However, the majority of items used in NE-Atlantic aquaculture practices (e.g. feeding pipes, netting, ropes/cords, buoys etc.) are either not exclusively used by aquaculture facilities, and therefore cannot be assigned to the aquaculture sector as a definite source, or can only be assigned to a more general category under the OSPAR guidelines. This creates an underestimation of items directly attributed to the aquaculture sector in the OSPAR beach litter monitoring database (Sandra et al., 2020) and is confirmed by the beach litter analyses conducted as part of this study. The problem can be partly resolved with more flexibility and detailed categorization of litter in official reporting systems, use of local knowledge and in-depth beach litter analysis techniques such as the Litter-ID method (Sandra et al., 2020; Strietman et al., 2021).

4.2. Use local knowledge and engage stakeholders

Governmental or NGO-driven beach litter monitoring programs face difficulties with not only quantification, but also source identification of plastic pollution from aquaculture for several reasons. Organized and unorganized litter collections by beach walkers and community groups can interfere with the quantification process by partially removing litter from beaches (Buckingham et al., 2020). Moreover, the use of fishing gear in aquaculture often create difficulties in accurately distinguishing the source of the plastic waste between the two sectors. The engagement of local experts can help identify secluded areas in the right geographic locality for better assessments of beach litter related to aquaculture (e.g. near aquaculture sites or in the direction of sea currents from aquaculture sites). This was also the approach employed in the Old Dorney Habour beach litter analysis.

As already alluded to, a comprehensive in-depth monitoring system such as the Litter-ID method can be used to overcome shortcomings related to source identification, involving the participation of interest groups, local stakeholders and industry experts alike. This is particularly exemplified in the Griend beach litter analysis where the link between bucket lids and onion bags used in mussel culture could not have been made without local expert knowledge (Strietman et al., 2020).

Similarly, more general solutions to the causes of plastic pollution from aquaculture can also benefit from the engagement of local stakeholders. Litter workshops and stakeholder consultations that involve participants from all stages of the life cycle of aquaculture farming, like those conducted as part of the AQUA-LIT project, can provide valuable insights to preventing and addressing the plastic pollution problem as discussed further below (De Raedemaecker et al., 2020). Moreover, experience and expertise in the field are especially important in providing practical assessments on which solutions are feasible – economically, financially and time-effectively – and which are not.

4.3. Countering gear loss

One of the main causes of lost gear identified during the stakeholder participative process (i.e. interviews, consultations and workshop) is how consumable the gear is. Farmers are less likely to exercise extra caution in preventing cheaper gear intended for single or short-term use from being lost at sea. Possible solutions to addressing the problem could take the form of government regulations in prohibiting single-use plastics in fisheries and aquaculture, or ways in making gear more valuable to farmers (e.g. taxes on cheap disposable plastics). For less consumable gear, ideas of tracking and tracing were discussed at the AQUA-LIT workshop, including GPS tracking on buoys and other larger pieces of equipment (De Raedemaecker et al., 2020). Given cost of current technologies available, uptake by farmers is likely to be limited as tracking options are still too expensive.

In addition to the idea of track and trace for aquaculture gear and equipment, another solution suggested by Cole et al. (2019) is gear marking and tagging. The authors suggested that having the owner’s ID marked on gear and equipment might discourage intentional discarding at sea, as well as allowing for the possibility of returning the gear to the owner once found. For a more punitive approach, gear marking can also provide a practical approach to fine owners for losing gear (Cole et al., 2019).

4.4. Removal and recycling

The last line of response to the problem of plastic pollution from aquaculture is waste management. One of the key barriers to recycling of aquaculture gear is the economic cost and accessibility to such services. Stakeholders and industry interviewees raised a number of suggestions that centered around government support and producer responsibility. For example, to improve access to recycling services, government initiatives to make waste and recycling points available at harbors, including those in remote areas, is one potential solution (De Raedemaecker et al., 2020). Another is to introduce a deposit system with suppliers of gear and equipment, not dissimilar to that for plastic bottles scheme at European supermarkets (Rijksoverheid, 2020). This will not only improve accessibility through supplier responsibility, but also provide farms with an economic incentive to bring back old nets, cages, pipes and so forth. From the aspect of aquaculture producers, cooperation between offshore industries, including oil and gas companies, can help to reduce the cost of recycling. Similar cooperation across industries in remote areas are already seen in places like northern Scotland (pers. comm. with Scottish salmon companies 2019). Last but not least, further advancements in technological may also make it more attractive to recycle – in particular, better capabilities in retaining the quality of plastic in recycled products or a reduced need to clean gear prior recycling would make recycling more economically viable.

5. Conclusions and recommendations

Plastic pollution from aquaculture is an issue of growing concern. While the scale of plastic pollution does not match that from other sectors at the current time, it is expected to increase in the future as the aquaculture sector expands. Increasing restrictions from governments on farming in inshore areas are pushing companies to farm further offshore. This has the downside of increasing opportunities for plastic materials to end up as litter due to higher susceptibility to rough weather conditions, and higher costs to monitor offshore sites. It is critical that the pathways of plastic pollution are addressed to mitigate or reduce the impact on the marine environment.

The bright side to the plastic problem is that unlike commercial fishing, aquaculture is subject to greater control, and this allows for gear to be more easily managed and recovered when released (Schoof and DeNike, 2017). As such, macro-plastic pollution from aquaculture practices stands a better chance of being addressed. In this paper several solutions to the various pathways and challenges are discussed, and the recommendations made are summarized as follows:

- Industry: taking farm or sector level responsibility to coordinate within and across sectors in joint recycling programs, and adopting best practices such as trialing alternative (bio-)gear and materials.
- Governments: improving access to recycling facilities, promoting innovation and research around solutions such as alternative materials or applications of recycled plastics, using the macroeconomic tools (e.g. taxation and subsidies) to regulate production of plastic products. Other potential policy instruments include regulations on Single-Use Plastics, as well as Extended Producer Responsibly (EPR) for suppliers of plastic materials to the sector.
- Other key stakeholders such as NGOs and certification bodies: raising public awareness on the issue to put pressure on governments and industry in addressing the plastic problem. Employ transparent methods of identifying and tracing litter (e.g. gear tagging) in the certification process to generate consumer trust.

Finally, addressing plastic pollution from aquaculture cannot be tackled without adequate environmental monitoring and accounting systems in place at the national and regional level. Better insight into the composition, origin and pathways of marine litter is needed through more in-depth beach and seabed litter analysis. In-depth litter analysis techniques, similar to the Litter-ID method, could be applied in addition to ongoing marine litter monitoring efforts in order to gain such insights. Finally, ensuring consistency and comparability across regions is key to understanding trends in aquaculture pollution over time and across regions. This is especially true for litter that have been shown to travel large distances, where the particular type of farming installation is not typically used (e.g. Tahitians found on the Dutch coastlines from aquaculture practices common to France). This can be achieved through improved cooperation and harmonization across monitoring programs such as OSPAR, HELCOM and other marine litter data networks.

CRediT authorship contribution statement

Maggie Skirtun: Conceptualization, Data curation, Formal analysis, Writing – original draft, Writing – review & editing, Visualization, Project administration, Supervision. **Matthias Sandra:** Writing – review & editing, Methodology, Formal analysis, Validation. **Wouter Jan Strietman:** Conceptualization, Methodology, Data curation, Formal analysis, Writing – original draft, Writing – review & editing, Visualization. **Sander W.K. van den Burg:** Conceptualization, Writing – original draft, Writing – review & editing, Visualization, Funding acquisition. **Fien De Raedemaecker:** Writing – review & editing, Validation, Funding acquisition. **Lisa I. Devriese:** Writing – review & editing, Validation, Funding acquisition.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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References

Atkins, J.P., Burdon, D., Elliott, M., Gregory, A.J., 2011. Management of the marine environment: integrating ecosystem services and societal benefits with the DPSIR framework in a systems approach. Mar. Pollut. Bull. 62 (2), 215–226.
Boyle, D., Catarino, A.I., Clark, N.J., Henry, T.B., 2020. Polyvinyl chloride (PVC) plastic fragments release Pb additives that are bioavailable in zebrafish. Environ. Pollut. ISSN: 0269-7491 263 (Part A) https://doi.org/10.1016/j.envpol.2020.114422.
Buckingham, J., Capper, A., Bell, M., 2020. The missing sink - quantification, categorisation and sourcing of beached macro-debris in the Scottish Orkney Island. Mar. Pollut. Bull. 157, 111364.
Butterworth, A., Clegg, I., Bass, C., 2012. Untangled, Marine Debris: A Global Picture of the Impact on Animal Welfare and of Animal-Focused Solutions. World Society for the Protection of Animals, London.
Cole, G., Thomas, B., Jones, B., Hargreaves, S., Chambers, K., Powell, K., Walker, H., 2019. Mapping economic, behavioural and social factors within the plastic value chain that lead to marine litter in Scotland. Commercial fishing gear report, Resource Future, prepared for the Scottish Government. Available online: https://www.gov.scot/binaries/content/documents/govscot/publications/research-and-analysis/2020/02/mapping-economic-behavioural-social-factors-within-marine-plastic-value-chain-scotland/documents/commercial-fishing-gear/commercial-fishing-gear/govscot%3Adocument/commercial-fishing-gear.pdf.
De Raedemaecker, F., Sandra, M., Devriese, L., Gin, I., Altvater, S., Vidal Rigo, M., Alomar, C., Deudero, S., Mata Lara, M., 2020. Learning Lab report North Sea. D3.4 Aqua-Lit project, 72 pp. Flanders Marine Institute (VLIZ), Oostende. http://www.vliz.be/nl/imis?module=ref&refid=328675.
Det Norske Veritas (DNV), 2021. Marine Aquaculture Forecast to 2050. https://www.dnv.com/focus-areas/offshore-aquaculture/marine-aquaculture-forecast/index.html#.
Devriese, L., van der Meulen, M.D., Maes, T., Bekaert, K., Paul-Pont, I., Frère, L., Robbens, J., Vethaak, A.D., 2015. Microplastic contamination in brown shrimp (Crangon crangon, Linnaeus 1758) from coastal waters of the Southern North Sea and Channel area. Mar. Pollut. Bull. 98 (1–2), 179–187. https://doi.org/10.1016/j.marpolbul.2015.06.051.
Devriese, L., De Witte, B., Vethaak, A.D., Hostens, K., Leslie, H.A., 2017. Bioaccumulation of PCBs from microplastics in Norway lobster (Nephrops norvegicus): an experimental study. Chemosphere 186 (Nov), 10–16. https://doi.org/10.1016/j.chemosphere.2017.07.121.
European Commission (EC), 2012. Fisheries and aquaculture in Europe, No. 58, 2012. available at. https://ec.europa.eu/fisheries/cfp/aquaculture/species.
European Environmental Agency (EEA), 1997. Air Pollution in Europe. Copenhagen, ISBN 92-9167-059-6. https://www.eea.europa.eu/publications/92-9167-059-6-sum.
European Market Observatory for Fisheries and Aquaculture Products (EUMOFA), 2019. The EU fish market: 2019 Edition. available at. Publications Office of the European Union, Luxembourg, ISBN 978-92-76-12174-9. https://www.eumofa.eu/documents/20178/314856/EN_The+EU+fish+market_2019.pdf/.

Foekema, E.M., De Gruijter, C., Mergia, M.T., Van Franeker, J.A., Murk, T.J., Koelmans, A.A., 2013. Plastic in North Sea fish. Environ.Sci.Technol. 47, 8818–8824.
Food and Agriculture Organization (FAO), 2020a. Fisheries and Aquaculture Statistics 2018. FAO Yearbook, Rome. https://doi.org/10.4060/cb1213t.
Food and Agriculture Organization (FAO), 2020b. The State of World Fisheries and Aquaculture (SOFIA), Sustainability in Action, Rome. https://doi.org/10.4060/ca9229en.
Food and Agriculture Organization (FAO), 2021. Fisheries Statistical Collections: Global Aquaculture Production (Webpage last accessed 4/11/2021). http://www.fao.org/fishery/statistics/global-aquaculture-production/en.
Gin, I., Lheureux, G., Altvater, S., De Raedemaecker, F., Devriese, L., Mata Lara, M., Sandra, M., Vidal Rigo, M., Alomar, C., Deudero, S., 2020. Learning Lab outcome. Portfolio of best practice fact sheets, 93 pp. available online at:. D3.5 Aqua-Lit project, Nausicaá: Wimereux https://aqua-lit.eu/assets/content/D3.5_Best_practice_factsheets_watermark.pdf.
Global Ghost Gear Initiative, 2021. Best Practice Framework for the Management of Aquaculture Gear, 81 pp. plus appendices. Prepared by Huntington, T. of Poseidon Aquatic Resources Management Ltd. for GGGI. https://repository.oceanbestpractices.org/handle/11329/1728.
Heo, N.W., Hong, S.H., Han, G.M., Hong, S., Lee, J., Song, Y.K., Jang, M., Shim, W.J., 2013. Distribution of small plastic debris in cross-section and high strandline on Heungnam Beach,South Korea. Ocean Sci. J. 48 https://doi.org/10.1007/s12601-013-0019-9.
Hinojosa, I., Thiel, M., 2009. Floating marine debris in fjords, gulfs and channels of southern Chile. Mar. Pollut. Bull. 58, 341–350.
Hipólito, C., Vale, M., Devriese, L., Paramio, L., 2020. Policy Recommendations to Tackle Aquaculture Debris. Deliverable 5.1. developed by FRCT under the AQUA-LIT Project (GA. EASME/EMFF/2017/1.2.1.12/S2/04/S12.789391), Azores, 32pp.
Huntington, T., 2019. Marine Litter and Aquaculture Gear – White Paper. Report produced by Poseidon Aquatic Resources Management Ltd for the Aquaculture Stewardship Council, 20 pp plus appendices.
Jacobsen, J.K., Massey, L., Gulland, F., 2010. Fatal ingestion of floating net debris by two sperm whales (Physeter macrocephalus). Mar. Pollut. Bull. 60, 765–767.
Jambeck, J.R., Geyer, R., Wilcox, C., Siegler, T.R., Perryman, M., Andrady, A., Narayan, R., Lavender Law, K., 2015. Plastic waste inputs from land into the ocean. Science 347, 768–771.
Koelmans, A.A., Bakir, A., Burton, A., Janssen, C.R., 2016. Environ. Sci. Technol. 50 (7), 3315–3326. https://doi.org/10.1021/acs.est.5b06069.
Kristensen, P., 2004. The DPSIR Framework. Land Resources Planning Toolbox. Food and Agriculture Organization of the United Nations. http://www.fao.org/land-water/land/land-governance/land-resources-planning-toolbox/category/details/en/c/1026561/.
Kühn, S., Bravo Rebolledo, E.L., Van Franeker, J.A., 2015. Deleterious effects of litter on marine life. In: Bergmann, M., Gutow, L., Klages, M. (Eds.), Marine Anthropogenic Litter. Springer, Berlin. https://doi.org/10.1007/978-3-319-16510-3_4.
Lavender Law, K., Morét-Ferguson, S., Maximenko, N.A., Proskurowski, G., Peacock, E. E., Hafner, J., Reddy, C.M., 2010. Plastic accumulation in the North Atlantic subtropical gyre. Science 329, 1185–1188.
Lusher, A.L., McHugh, M., Thompson, R.C., 2013. Occurrence of microplastics in the gastrointestinal tract of pelagic and demersal fish from the English Channel. Mar. Pollut. Bull. 67, 94–99.
Lusher, A., Hollman, P., Mendoza-Hill, J., 2017. Microplastics in fisheries and aquaculture: status of knowledge on their occurrence and implications for aquatic organisms and food safety. Available online:. FAO Fisheries and Aquaculture Technical Paper, ISBN 978-92-5-109882-0, United Nations Food and Agriculture Organization http://www.fao.org/3/I7677E/I7677E.pdf.
Marine Scotland, 2015. A Technical Standard for Scottish Finfish Aquaculture. available at:. Developed by the Ministerial Group for Sustainable Aquaculture's Scottish Technical Standard Steering Group, Published by the Scottish Government, ISBN 978-1-78544-372-5 https://www.gov.scot/publications/technical-standard-scottish-finfish-aquaculture/.
Maxim, L., Spangenberg, J.H., O'Connor, M., 2009. An analysis of risks for biodiversity under the DPSIR framework. Ecol. Econ. 69 (1), 12–23.
Mowi, 2020. Mowi Integrated Annual Report 2020. Bergen, Norway. 312pp. https://mowi.com/blog/annual-report-2020/.
Murray, F., Cowie, P.R., 2011. Plastic contamination in the decapod crustacean Nephrops norvegicus (Linnaeus, 1758). Mar. Pollut. Bull. 62, 1207–1217. https://doi.org/10.1016/j.marpolbul.2011.03.032.
OSPAR, 2010. Guideline for monitoring marine litter on the beaches in the OSPAR maritime area. OSPAR Commission. https://www.ospar.org/ospar-data/10-02e_beachlitter%20guideline_english%20only.pdf.
OSPAR CEMP, 2020. Guidelines for marine monitoring and assessment of beach litter. OSPAR Commission. https://www.ospar.org/documents?v=44122.
Parker, L., 2019. The world's plastic pollution crisis explained, National Geographic article, 7 June 2019. https://www.nationalgeographic.com/environment/article/plastic-pollution.
Patrício, J., Elliott, M., Mazik, K., Papadopoulou, K.-N., Smith, C.J., 2016. DPSIR — two de-cades of trying to develop a unifying framework for marine environmental management. Front. Mar. Sci. 3.
Richens, J., 2020. Can sustainable aquaculture feed the world?, Reuters Events article, published 26 August 2020. https://www.reutersevents.com/sustainability/can-sustainable-aquaculture-feed-world.
Rijksoverheid, 2014. C-171 Fishery for a Clean Sea Green Deal. Online: https://www.greendeals.nl/green-deals/visserij-voor-een-schone-zee.
Rijksoverheid, 2018. Korte uitleg DPSIR methode. https://www.helpdeskwater.nl/onderwerpen/wetgeving-beleid/kaderrichtlijn-water/uitvoering/rijn-west/we/krw/dpsir/.
Rijksoverheid, 2020. Deposit on small plastic bottles to reduce street litter, News item 30/04/2020. https://www.government.nl/latest/news/2020/04/30/deposit-on-small-plastic-bottles-to-reduce-street-litter.
Rochman, C.M., Tahir, A., Williams, S.L., Baxa, D.V., Lam, R., Miller, J.T., Teh, F.C., Werorilangi, S., Teh, S.J., 2015. Anthropogenic debris in seafood: plastic debris and fibers from textiles in fish and bivalves sold for human consumption. Sci. Rep. 5, 14340. https://doi.org/10.1038/srep14340.
Sandra, M., Devriese, L.I., De Raedemaecker, F., Lonneville, B., Lukic, I., Altvater, S., Compa Ferrer, M., Deudero, S., Torres Hansjosten, B., Alomar Mascaró, C., Gin, I., Vale, M., Zorgno, M., Mata Lara, M., 2020. Knowledge wave on marine litter from aquaculture sources. D2.2 Aqua-Lit project. (Updated version). Flanders Marine Institute (VLIZ), Oostende, 136 pp.
Schoof, R., DeNike, J., 2017. Microplastics in the context of regulation of commercial shellfish aquaculture operations: microplastics in the context of regulation of aquaculture, 93 pp. available online at: Integrated Environ. Assess. Manag. 13, 522–527. https://doi.org/10.1002/ieam.1905.
Scientific, Technical and Economic Committee for Fisheries (STECF), 2018. Economic Report of the EU Aquaculture Sector (STECF-18-19). Publications Office of the European Union, Luxembourg, ISBN 978-92-79-79402-5. https://doi.org/10.2760/45076. JRC114801.
Scopus abstract and citation database, 2021. Available at. https://www.scopus.com. last accessed 4 Nov 2021.
Sherrington, C., Darrah, C., Cole, G., Corbin, M., Hann, S., 2016. Study to support the development of measures to combat a range of marine litter sources. In: Report for European Commission DG Environment. EUNOMIA, 429 pp.
Strietman, W.J., van den Heuvel-Greve, M.J., van den Brink, A., de Groot, A., Skirtun, M., Bravo-Rebolledo, E., 2020. Resultaten bronanalyse zwerfafval Griend: Resultaten van een gedetailleerde bronanalyse van zwerfafval dat op het Waddeneiland Griend verzameld is en samen met lokale stakeholders tijdens een Litter-ID-sessie in oktober 2019 onderzocht is. https://doi.org/10.18174/528599.
Strietman, W.J., van den Heuvel-Greve, M., van den Brink, A., Leemans, E., Strand, J., Bach, L., 2021. Beach litter in North-West Greenland: A Source Analysis. https://doi.org/10.18174/541149.
Van Cauwenberghe, L., Janssen, C.R., 2014. Microplastics in bivalves cultured for human consumption. Environ. Pollut. 193, 65–70. https://doi.org/10.1016/j.envpol.2014.06.010.
Van Sebille, E., et al., 2020. The physical oceanography of the transport of floating marine debris. Environ. Res. Lett. 15 (2), 023003. https://iopscience.iop.org/article/10.1088/1748-9326/ab6d7d/pdf.
Veiga, J.M., Fleet, D., Kinsey, S., Nilsson, P., Vlachogianni, T., Werner, S., Galgani, F., Thompson, R.C., Dagevos, J., Gago, J., Sobral, P., Cronin, R., 2017. Identifying Sources of Marine Litter. MSFD Technical Group Marine Litter - Thematic Report. JRC Technical Report. Online:. European Commission, Joint Research Centre. EUR28309 EN. https://doi.org/10.2788/018068 https://ec.europa.eu/environment/marine/good-environmental-status/descriptor-10/pdf/MSFD_identifying_sources_of_marine_litter.pdf.
Werner, S., Budziak, A., van Franeker, J., Galgani, F., Hanke, G., Maes, T., Matiddi, M., Nilsson, P., Oosterbaan, L., Priestland, E., Thompson, R., Veiga, J., Vlachogianni, T., 2016. Harm Caused by Marine Litter. MSFD GES TG Marine Litter - Thematic Report, JRC Technical Report. https://doi.org/10.2788/690366.
Wilcox, C., Sebille, E., Hardesty, B., 2015. Threat of plastic pollution to seabirds is global, pervasive, and increasing. Proc. Natl. Acad. Sci. 112. https://doi.org/10.1073/pnas.1502108112.
Wyles, K.J., Pahl, S., Thomas, K., Thompson, R.C., 2016. Factors that can undermine the psychological benefits of coastal environments: exploring the effect of tidal state, presence, and type of litter. Environ. Behav. 48 (9), 1095–1126. https://doi.org/10.1177/0013916515592177.