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Using Material Flow Analysis (MFA) to generate the evidence on plastic waste management from commercial fishing gears in Norway

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ABSTRACT

Plastic debris is an ever-growing concern adversely affecting the coastal and marine ecosystem. Among marine plastic waste, a particularly troublesome waste fraction is Abandoned, Lost or Discarded Fishing Gears (ALDFG) that continues to trap marine life for years upon releaseand has significant adverse environmental effects on coastal and marine ecosystems. However, lack of scientific data on the estimated contribution of ALDFG to marine plastics and associated reasoning hinders the management of fishing gear resources across the globe. This study presents a system-wide analysis of the typical fishing gears used in Norway for commercial fishing, i.e. trawls, seines (Danish and Purse), longlines, gillnets, and traps. Based on data from gear producers, suppliers, fishers, collectors, authorities, and waste management facilities, we model the flows of plastics polymers, polypropylene, polyethylene, and Nylon, used as the building blocks of advanced gears. A static Material Flow Analysis (MFA) is used to understand life cycle processes and further monitor gear quantities in and between the processes in the system. Our findings indicate that commercial fishing in Norway contributes to around 380 t/yr. mass of plastics from lost fishing gears and parts. Gillnets, longlines, and traps are the main contributors to ALDFG in the ocean due to gear design, practice, and ground deployment. Additionally, around 4000 tons of plastic waste is collected in Norway annually from derelict fishing gears out of which 24% is landfilled, and 21% is incinerated for energy recovery. The MFA approach shows significant potential as a holistic decision support tool for industry and policy-makers in exercising sustainable fishing gear resource management. The study also generates key evidence on regional level plastic pollution from the fishing sector and highlights possible mechanisms that may aid in proposed improvements.

1. Introduction

Globally, oceans continue to accumulate debris of all forms, making them the biggest landfill on the planet (Schneider et al., 2018). Marine littering, defined as any persistent, manufactured or processed solid refuse discarded, disposed of or abandoned in the marine or coastal environment through human activity, is a growing concern for authorities (Galgani et al., 2010). The scientific reviews conducted by Moore (2008) highlighted the apparent predominance of plastics amongst marine litter, contributing 60%–80% of total marine debris around the globe. A more recent study estimates an annual influx of between 4.8-12.7 million tons of plastic waste entering the ocean (Jambeck et al., 2015) and forming the notable garbage patches in global waters (Lebreton et al., 2018).

Among the total plastic waste entering the oceans, a particularly troublesome waste fraction is Abandoned, Lost or Discarded Fishing Gears (ALDFG) that may continue to trap marine animals for decades upon release (Laist, 1997, Macfadyen et al., 2009). Since fishing gear (FG) made of plastic polymers has a long lifespan and is designed to capture marine organisms, ALDFG is considered one of the most hazardous waste fractions for marine animals (Wilcox et al., 2016). A common problem is ghost fishing, where abandoned, lost or discarded gears, such as gillnets, trammel nets, seines, trawls, and pots, continue to catch fish, crustaceans, birds, mammals and reptiles (Laist, 1997, Brown and Macfadyen, 2007). The amount, distribution and effects of ALDFG have risen substantially over past decades with the rapid expansion of fishing efforts and fishing grounds, and the transition to synthetic, more durable and more buoyant materials used for FG (Derraik, 2002, Gilman, 2015). Upon deployment, FGs may get lost for a variety of reasons including (but not limited to) adverse weather conditions, irregular topography, gear conflicts and failures, ship collisions, abandonment, human error, and vandalism. Such events are the most common causes contributing to the ALDFG problematic (Graeme Macfadyen, 2009, Richardson et al., 2018).

Previous studies demonstrate the deleterious effects of ALDFG on marine ecosystems. Detailed studies investigated problematics including entanglement (Stelfox et al., 2016, Yoshikawa and Asoh, 2004, Laist, 1997), navigational hazards (Hong et al., 2017), impacts on coral reefs (Chiappone et al., 2005, Chiappone et al., 2002, Cho, 2011), and the risk of bioaccumulation through micro-plastics (Chen et al., 2018, Browne et al., 2015, Browne et al., 2010, Foekema et al., 2013, Phillips et al., 2010, Koelmans et al., 2017). In comparison, we know very little

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of the extent of ALDFG pollution generated by commercial fisheries. Jambeck et al. (2015) highlight the knowledge deficiency of plastic flows from fishing activities in the quantification of the total plastic in marine debris.

In EU member states, commercial fishing is a primary activity in which wastes from FGs are regulated through a range of international and regional instruments including United Nations Convention on the Law of the Sea (UNCLOS), London Convention, OSPAR, MARPOL Annex V, EU Waste Framework Directive and EU Marine Strategy Framework Directive (Chen, 2015). Additionally, to reduce the impact of marine plastic on the environment, the EU is committed to improving the collection of fishing equipment containing plastics and highlights opportunities to establish circular business models (EC, 2018b). Nevertheless, there is a lack of monitoring tools to estimate the amount of plastics in ALDFG that enters the ocean and is available after end-of-life (EOL) collections. To build robust resource management strategies and realize sustainable circular business opportunities that are capable of utilizing untapped resources across regions, it is essential to know the amount of plastic available for recycling from the fishing sector.

In this study, Material Flow Analysis (MFA) is applied to track physical flows and stocks of mass of plastic (MoP) from FGs in Norway through use and post-use processes. Based on data from gear producers, fishers, collectors, and recycling and waste management companies, a static MFA model is established to quantify the annual stocks and flows of plastic polymers (PP, PE, and Nylon) from the FGs deployed by the Norwegian fishing fleet.

2. Materials and Methods

2.1. Material flow analysis

The basic principle of MFA is the conservation of matter and energy in isolated systems, delimited by boundaries of time and space and following the mass-balance principle (Brunner and Rechberger, 2004). It is a decision-support tool for evaluating technology efficiency and industrial practices, and for managing resources and environmental impacts (Brunner and Rechberger, 2004). Typically, MFA of a selected substance includes the main life cycle stages namely, mine, production, manufacturing, use, maintenance and disposal (Habib et al., 2014). We used MFA to measure the annual loads of plastic evolving through the life cycle of commercial FG in Norway. This study focuses solely on the Norwegian commercial fishing fleet, through both use and post-use processes. The MFA model was built to present the 2016 stocks and flows of plastics from FGs because of the maximum data availability obtained through data collection rounds. Static models provide insight into systems at a specific time, allowing holistic assessment of their current state (Allesch and Brunner, 2017, Van Eygen et al., 2017). Primary modeling and flow calculations were performed in Microsoft Excel, while STAN v2.6.8 was used for further data reconciliation (Vienna University of Technology, Vienna, Austria). Information on key processes, data collection methods and selected FGs are elaborated in the following sections.

2.2. System Description

In this study, the term Fishing gear (FG) is defined as "any physical device or part thereof or combination of items that may be placed on or in the water or on the seabed with the intended purpose of capturing or controlling for subsequent capture or harvesting, marine or freshwater organisms whether or not it is used in association with a vessel" (FAO, 2016). Throughout the text, the term "plastics" includes polyethylene (PE), polypropylene (PP) and Nylon. These three polymers are the main building blocks in the production of modern synthetic FGs (Baeta et al., 2009, Brown and Macfadyen, 2007). Fig. 1 represents the common life cycle processes of commercial FGs used by the Norwegian fishing fleet. In this study we include six major commercial FGs, namely trawls, purse seines, Danish seines, gillnets, longlines, traps/pots, and their associated ropes.

FGs are divided into two categories, active and passive. Active gears (seines and trawls) dynamically hunt the targeted species whereas, passive gears (lines, gillnets and traps/pots) are fixed gears aimed to catch active fish (Muus and Nielsen, 1999). Passive gears are economically cheap making them popular among small-scale fishers. The system boundaries are set to include the annual life cycle processes of FGs deployed by the Norwegian commercial fishing fleet. Commercial fishing from international vessels and leisure fishing from private vessels in Norwegian waters are excluded.

The commercial fishing fleet of Norway is controlled by The Norwegian Directorate of Fisheries (Fiskeridirektoratet, 2017). Every year, fishing companies purchase FGs mainly to equalize the stock after annual losses from deployment or disposal after end-of-life. In the use-phase, fishers deploy FGs in the ocean to catch a target species. Deployed FGs, or their parts, may get lost during operation due to a variety of reasons listed by Graeme Macfadyen (2009). Although causes of FG loss upon deployment are well described by Graeme Macfadyen (2009), Richardson et al. (2018), limited information is available in the literature on the rates of gear loss resulting from fishing activities (Humborstad et al., 2003). Historically, Breen (1987) used fishers' responses to derive the annual rate of 11% trap loss in the Fraser River Estuary of British Columbia. The FANTRED study conducted by MacMullen (2002) remains the only attempt to estimate the rate of gillnets loss in European waters. However, these studies are obsolete, region-specific and limited to specific FG types, and therefore cannot be used in this study's context.

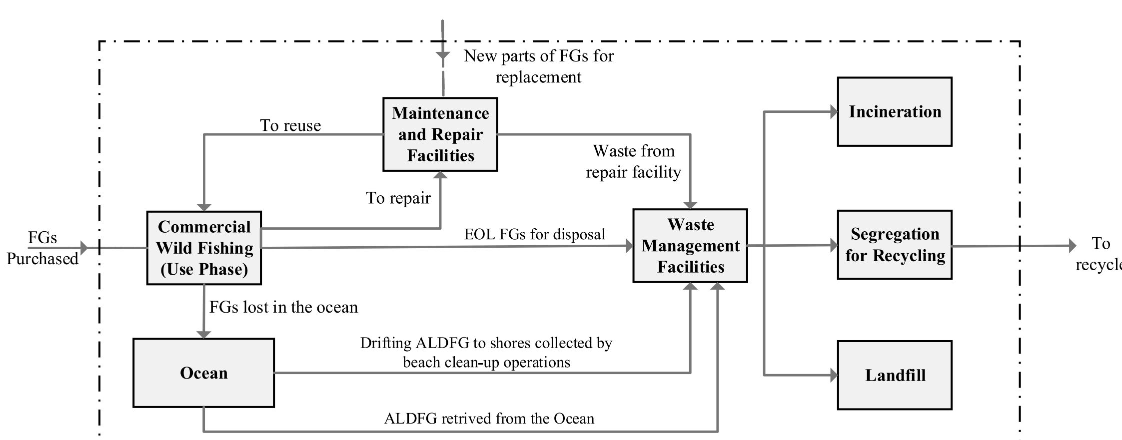

Fig. 1. Processes involved in the system life cycle of commercial FGs in Norway.

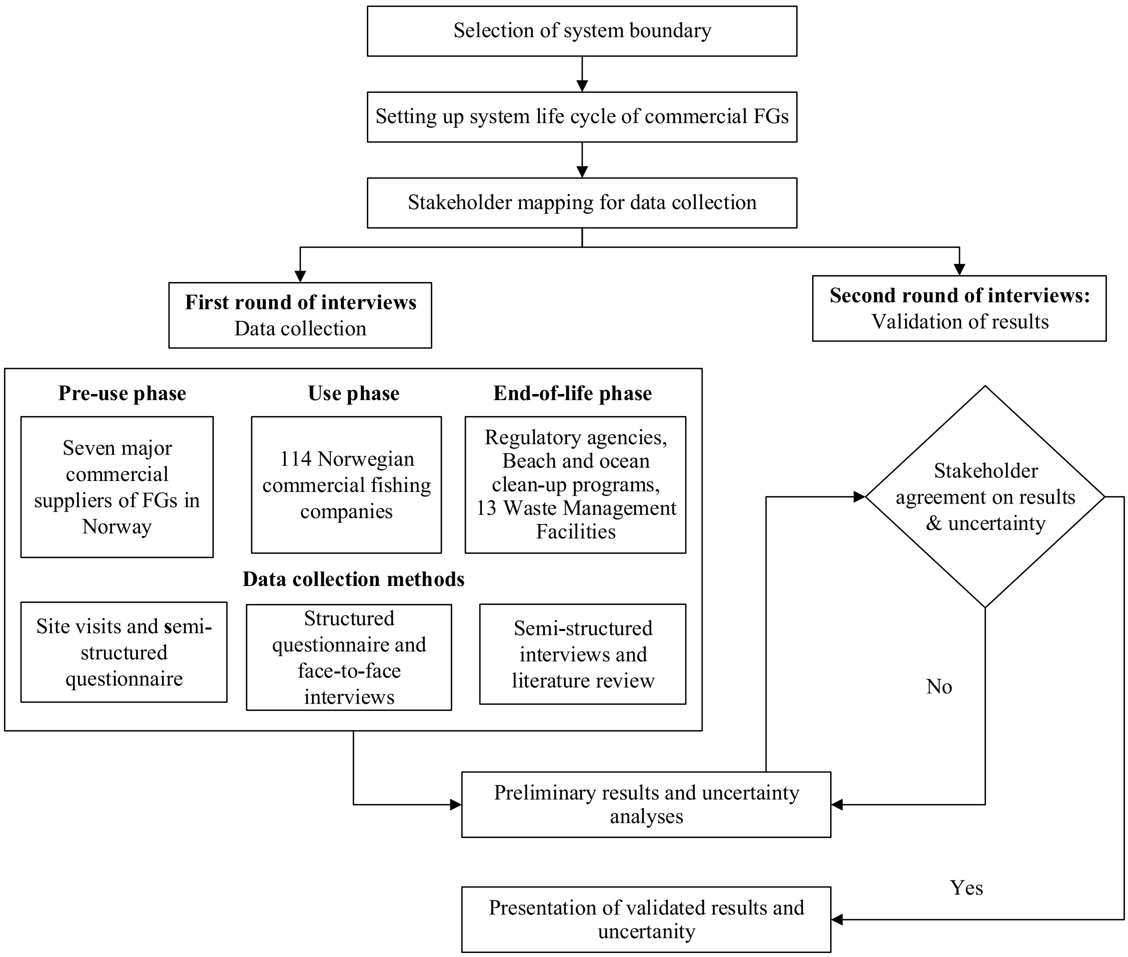

Fig. 2. Stepwise approach adapted for the collection and validation of MFA results.

Additionally, fishing activities cause wear and tear to the gear used, and consequently, fishers must frequently maintain and repair their FGs. Some repairs involve the replacement of damaged or lost parts. In this study, repairs that involve the replacement of FG part(s) are considered "major repairs." Major repairs need external intervention and are carried out by either the fishing company or the dedicated repair facilities managed by FG producers. It is essential to note that most FGs undergo continuous minor repairs after each fishing activity. Minor repairs include stitching, tying and adjusting broken parts of the gear without any significant replacement of parts. Such minor repairs are excluded in this system, as they have no significant impact on mass flows.

End-of-life pathways of FGs are manifold; firstly fishing companies' dispose of waste FGs to the nearest waste handling facilities. In addition, lost FGs and parts are retrieved through annual ocean clean-up surveys to minimize the risk of ghost fishing and associated damage to the marine environment. Furthermore, floating fractions of ALDFG end-up on shores, dragged by the wind and waves. Some of those FGs and gear residue are further collected during annual beach clean-up operations conducted across the Norwegian coastline. ALDFG collected from land and ocean ultimately end-up at Waste Management Facilities (WMF). Waste generated during FG repairs also ends up in WMFs. At the end of the value-chain, waste managers segregate waste FGs into different fractions, which include the recyclable fraction, the fraction for landfill and the incinerable fraction for energy recovery. The segregated fractions are then transported to their respective facilities. A detailed description of the commercial fishing fleet and selected FGs is presented in section S1 of the supplementary material.

2.3. *Data Collection*

Data collection took place from June 2017 to August 2018. Both top-down and bottom-up approaches were used to collect data for calculating flows and transfer coefficients. Fig. 2 shows the stepwise approach used for data collection, validation of MFA results and associated uncertainty. After identifying the system boundary and life cycle stages for commercial FGs, stakeholder mapping was conducted for targeted data collection. Data was primarily collected using published literature, government statistics, and interviews of stakeholders. Table 1 briefly describes the flows, stocks, equations and data sources used.

In the first round of interviews, information regarding sales volumes and compositions of each FG type were obtained from seven major suppliers and manufacturers of FGs in Norway. Using fishers' knowledge (FK) to estimate local patterns in fishing is common practice in natural resource management (Fischer et al., 2015, Hind, 2014, Johannes, 1998). The survey questionnaire was designed using a Delphi method that seeks the experts' consensus to bring clarity to the proposed questions. The questions were aimed at generating evidence on typical FG life-span, potential causes and rates at which gears are lost in the ocean upon deployment. Repair and reuse are identified as a primary strategy in the circular economy to slow-down the loop of a product lifecycle (EU, 2014). A well-established repair system allows for prolonged product life, which reduces waste generation and thereby promotes circularity in the system. Again, fishers' perception of managing FGs was deemed essential to understand the range of repair and reuse patterns of the six FG types. Survey questions were designed to gather the data to estimate the percentage of FGs owned by a fishing

Table 1
Description of flows, respective data sources and flow equations.

FLOW ORIGIN, SYMBOL	FLOW NAME	DESCRIPTION	DATA SOURCE	EQUATION
$F_{0,1}$	FGs purchased (t/yr)	Mass of Plastics (MoP) in purchased commercial FGs.	Fishing gear suppliers	Σ plastics in purchased FGs (Trawls, Purse Seine, Danish Seine, Gillnets, Longline and Traps)
$F_{1,2}$	FGs to major repair (t/yr)	MoP in FGs sent for major repairs including replacement of parts.	Fishers survey	$\Sigma\ C_{rep}{}^{*}\ FG_{owned}$
$F_{1,3}$	Lost FGs and parts (t/yr)	MoP in FGs entering in the ocean from lost FGs or parts upon deployment.	Fishers survey	$\Sigma\ C_{lost}{}^{*}\ FG_{owned}$
$F_{1,4}$	Worn FGs to disposal facility (t/yr)	MoP in end-of-life FGs disposed of by fishers at the WMFs or ports.	Fishers survey	$\Sigma\ C_{disp}{}^{*}\ FG_{owned}$
$F_{2,1}$	Repaired FGs to reuse (t/yr)	MoP in repaired FGs being reuse.	Mass balance	$F_{0,1}+S_1\text{-}F_{1,4}\text{-}F_{1,3}\text{-}F_{1,2}$
$F_{0,2}$	New FG parts for replacement (t/yr)	MoP in replacement parts used by repair facilities.	Fishers survey	$\Sigma\ C_{repair}{}^{*}\ C_{replace}{}^{*}FG_{owned}$
$F_{2,4}$	Waste FGs from the repair facility (t/yr)	MoP in the waste from FG generated during repair.	Mass Balance	$F_{0,2}+F_{1,2}\text{-}F_{2,1}$
$F_{3,4a}$	ALDFGs collected from beaches (t/yr)	MoP in the collected ALDFG from the beach clean-ups.	Keep Norway Beautiful (HNR)	
$F_{3,4b}$	ALDFGs retrieved from the ocean (t/yr)	MoP in the collected ALDFG from the ocean clean-ups.	The Norwegian Directorate of Fishery and Fishing for Litter.	
$F_{4,5}$	Waste FGs to incineration (t/yr)	MoP in collected waste FGs incinerated at the WMFs.	WMFs survey	$\Sigma\ C_{inc}{}^{*}\ (F_{2,4}+F_{1,4}+F_{3,4a}+F_{3,4b})$
$F_{4,6}$	Segregation and processing for recycling (t/yr)	MoP in collected waste FGs sent for recycling abroad.	WMFs survey	$\Sigma\ C_{rec}{}^{*}\ (F_{2,4}+F_{1,4}+F_{3,4a}+F_{3,4b})$
$F_{4,7}$	Waste FGs to landfill (t/yr)	MoP in collected waste FGs landfilled at the WMFs.	WMFs survey	$\Sigma\ C_{landfill}{}^{*}\ (F_{2,4}+F_{1,4}+F_{3,4a}+F_{3,4b})$
S_1+DS_1	Stock change of total FGs owned by commercial fishers (t)	MoP in the stocks of FGs owned by the Norwegian fishing fleet.	Fishers survey	$C_{turnover}{}^{*}\ F_{0,1}$
S_3+DS_3	Stock of ALDFG in the ocean (t)	MoP accumulating annually in the ocean as ALDFG.	Mass balance	$F_{1,3}\text{-}(F_{3,4a}+F_{3,4b})$

company that require major repair each year. In addition, the survey also determined the fraction of the total mass of FGs replaced during major repairs.

Face-to-face and telephonic interviews were conducted along Norway's six major ports. Answers from 114 commercial fishing companies were recorded and statistically analyzed to estimate the transfer coefficients of FGs flowing and stocked in the system. The formulae developed to estimate transfer coefficients and other methodological details adapted for fishers' survey are detailed in Deshpande et al. (2019).

In Norway, dedicated efforts are made to retrieve derelict FG from the ocean and beaches. Several voluntary actions are conducted throughout the year to collect and remove accumulated marine debris from the coastline (Falk-Andersson et al., 2019). One key stakeholder fighting against marine litter is Hold Norge Rent (HNR). HNR started as a project in 2012 to clean up Norwegian beaches, and went on to become an independent organization aiming to prevent environmental pollution by organizing volunteer clean-ups of trash and hazardous waste in nature (Jacob, 2016). Data on FG waste collected in beach clean-up activities from 2015 to 2017 in Norway was obtained through telephone interviews with the experts from these operations.

Information on FGs retrieved during ocean clean-up operations was obtained from the annual FG retrieval organized by the Norwegian Directorate of Fisheries and the Fishing for Litter (FFL) project. In Norway, commercial fishing vessels (size ≥ 28 meters) are required to report incidents that involve the loss of FGs and parts to the Coast Guard Central. This reporting includes specifications and geographical coordinates about the lost gear, and facilitates the Directorate of Fisheries' retrieval operations (Langedal, 2011). Under the FFL initiative, fishing vessels can deliver (free-of-charge) marine litter caught during regular fishing activity to collection points spread in specific harbors along the Norwegian coasts (Johnsen, 2017). The MoP from FGs collected through these schemes in the 2015 to 2017 period was gathered from the organizations' annual reports and interviews with the respective project managers.

In WMFs, waste is segregated and sent for landfilling, to incineration plants or to recycling facilities. For our questionnaire, we shortlisted 13 WMFs based on their proximity to harbors and ports. Then, the typical annual load of waste FGs received by the WMFs and the fractions of it sent for landfilling, incineration or recycling, was recorded. The questionnaires and responses from fishers, data from WMFs and other stakeholders, as well as statistical analysis and assumptions, are available in the supplementary material. Following data collection, a preliminary MFA model was built. In the second round of interviews, a preliminary MFA model was presented to all relevant stakeholders for validation. Finally, validated results and uncertainties were incorporated into the final MFA model presented in this study.

2.4. Uncertainty Analysis

Quantifying data uncertainty is a vital cog in justifying MFA results. As MFA demands the gathering, computing and harmonizing of physical flows and stocks from various sources with different data qualities, its results are inherently uncertain (Laner et al., 2014). In this study, standard statistical mean and the standard deviation were used to estimate the uncertainty of input variables. Further, uniform distributions are typically selected when it is possible to specify only a range of probable values. The probability distributions of the parameters and input data were used to estimate the probability distribution of the model outputs by applying Monte Carlo simulations (MCSs). The resulting histograms characterize the respective uncertainty associated with individual model outputs. The estimated output values of model flows, and the associated uncertainty through MCS iterations, were then further validated through STAN software to present the final values and uncertainties after data reconciliation (S3, supplementary data).

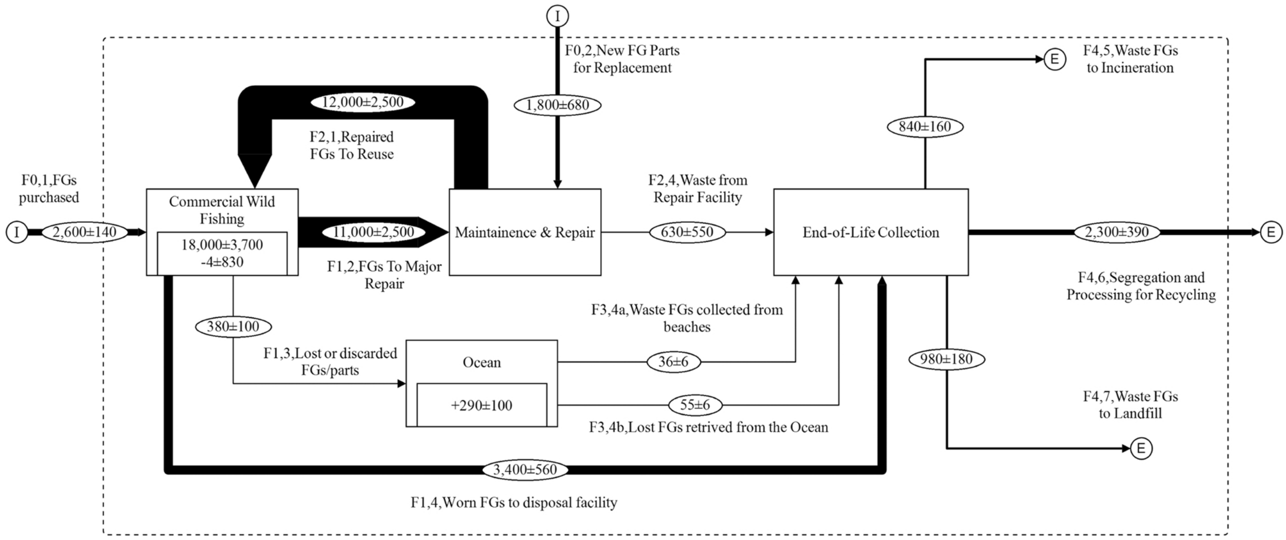

Fig. 3. MFA of plastic (PP, PE, and Nylon) from six fishing gears used by the commercial fishing fleet of Norway in 2016 (tons/yr).

3. Results

Fig. 3 presents the MFA of plastics from six types of FGs used annually by commercial fishers in Norway. Flows and stocks evolving in the system are calculated through the purchase, use and end-of-life phases of FGs.

3.1. Purchase phase

The total MoP in the form of newly purchased FGs ($F_{0,1}$) in 2016 is estimated to be 2626 ± 143 tons per year. Additionally, 1755 ± 681 tons of MoP is purchased as FG parts for replacement during major repairs ($F_{0,2}$). The weight of metal components in FGs, such as trawls, purse seines, Danish seines, and traps/pots, are excluded from the model calculations. The fishing fleet typically purchases the selected FGs to equalize their stock of owned FGs. Responses from 114 fishing companies were used to calculate the turnover coefficient of selected FGs. Such results in the estimated stock of FGs of 18413 ± 3676 tons MoP owned by the Norwegian fishing fleet.

3.2. Use phase

3.2.1. Repair Patterns

The responses from 114 fishers and typical repair-replace patterns for the six gears are presented in Fig. 4. Results indicate that repair of large and expensive gears such as trawls and purse seines is frequent, with more than 80% of total trawls and more than 50% of total purse seines subject to major repair every year. On the other hand, only one-third of the total owned inexpensive FGs, such as gillnets, traps/pots, and longlines, undergo major repairs.

Replacement of gear parts is a frequent process at repair facilities as parts of trawls, purse-, and Danish seines get lost and damaged during operation. The fishers' survey responses highlighted that FG types that undergo major repairs require the replacement of parts that make up 15% to 25% of the total mass of the gear. For instance, fishers informed us that during the deployment of trawls, they sometimes lose or damage the net extremity known as the 'cod-end.' Resultantly, they must replace the part, which represents 15% to 20% of the total weight of the gear, more often than any other parts of the trawl.

3.2.2. Deployment losses

Fishers reported the associated risk of damaging FGs and of losing part of or the entire gear upon deployment in the ocean. Survey responses showed that not all the commercial FG types are equally prone

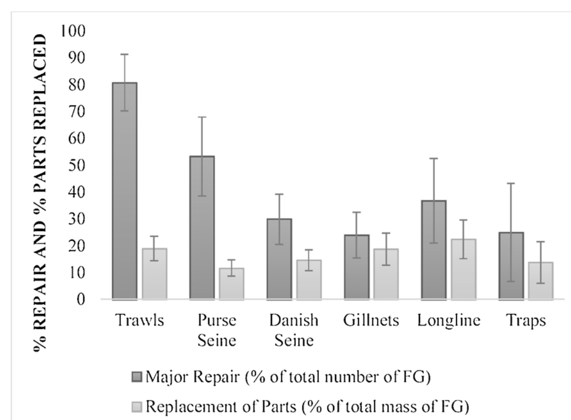

Fig. 4. Annual repair and replacement patterns of six commercial FGs used in Norway.

to get lost in the ocean. There are significant differences in their probabilistic loss rates. Additionally, it is important to note that the rate of FG losses estimated in this study only includes FGs that are lost upon deployment either accidentally or due to operational damage; deliberate abandonment of FGs are not considered in this study.

Responses from fishers within this study (Fig. 5) provide the annual loss rates of the six FGs and their parts occurring in Norwegian waters upon deployment.

It is evident that longlines and pots have higher chances of loss upon deployment. Indeed, around 4% to 7% of total longlines and traps/pots owned by the Norwegian fishing fleet ends-up in the ocean every year. Contrarily, purse seines and Danish seines are proven to be robust and safe gears that are rarely lost upon deployment. Gillnets are the primary source of derelict gears. Although only 1% to 2% of total gillnets are reportedly lost upon deployment, the amount of gillnets used by commercial fishers exceeds most other gears. Thus, lost gillnets also pose a significant threat to the marine ecosystem.

3.2.3. Typical disposal patterns of fishing gears

If not lost during operation or able to be repaired effectively or economically, fishers must dispose of FGs at their end-of-life. These EOL FGs are disposed either at port reception facilities or the nearest WMFs. Fishers' responses provided the operational life-span variability of the studied FGs. Sophisticated and expensive gears like purse seines and

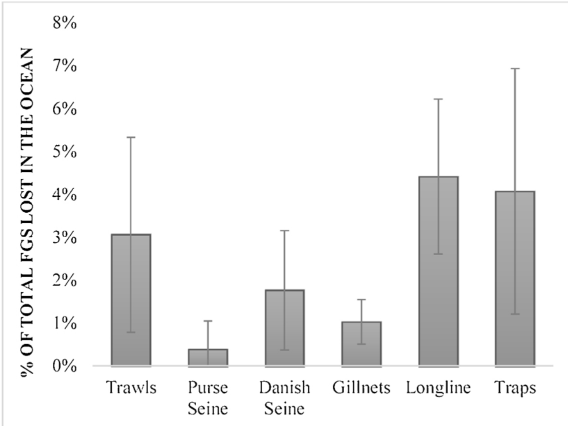

Fig. 5. Annual rates at which commercial fishers lost their FGs upon deployment.

Danish seines last the longest because of their fishing principal (slow deployment in the open sea) that minimizes wear and tear. FGs like gillnets and longlines, on the other hand, are cheap and display an operational life between 1-3 years implying frequent disposal. Consequently, almost one-third of gillnets and longlines, and one-fourth of trawls are disposed of by the fishing companies every year (Fig. 6).

3.3. End-of-Life Phase

3.3.1. Collection of gears from beaches and the ocean

Marine litter accumulated on the coastline is cleaned throughout the year through clean-up efforts. Analysis of the collected litter reveals that plastic from FGs constitutes up to 30% of the total marine litter found on the beaches in Norway (Jacob, 2016, Hartviksen, 2017). Personal interviews with managers of beach clean-up operations informed the estimation of the average weight-range of waste FGs collected during clean-up operations. The fraction of waste MoP removed from registered beach clean-up operations in Norway accounts for 36 tons per year ($F_{3,4a}$). This waste fraction is sent to the nearest WMFs for further management.

The amount of plastic collected through listed ocean clean-up operations was calculated from raw data, excluding metal and other non-plastic components of the FGs. An estimated 55 tons MoP is retrieved from Norwegian waters annually from the two ocean operations, annual gear retrieval surveys by the Norwegian Directorate of Fisheries and recovery of waste FGs through FFL ($F_{3,4b}$). It is impossible to know the source of these FGs and the year in which they entered the ocean.

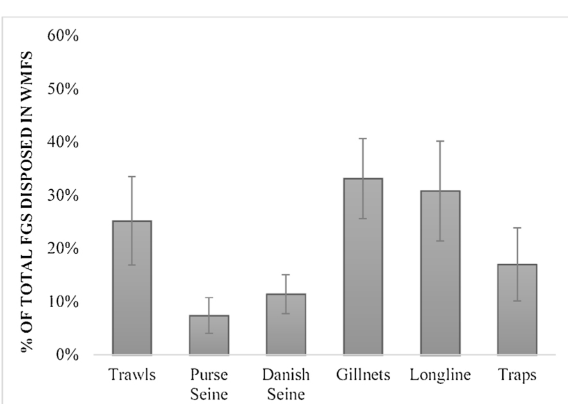

Fig. 6. Annual rates at which commercial fishers dispose of their gears to the WMFs.

3.3.2. Handling of FGs by WMFs

All the flows of waste FGs from fishers, repair facilities, and collected from land and water ends-up in the nearest WMFs. Responses from 13 WMFs were recorded, from which patterns of handling waste FGs were derived. Around 55% of the total FGs collected by WMFs are segregated and sent to recyclers for further processing, whereas 21% are sent for incineration and 24% are landfilled in Norway. It is essential to note that although 55% of the collected FG waste is sent for recycling, the fraction of waste generated during the recycling process and the recycling inefficiencies are excluded. Both the chemical and mechanical recycling of PP, PE, and Nylon take place out of Norway, and therefore, are considered out of scope for this study.

4. Discussion

4.1. Stock of plastics from FGs in the ocean

Despite stricter controls of fishing practices, our MFA shows that an estimated 380 ± 104 tons MoP is lost in the ocean annually by the Norwegian fishing fleet, which actively contributes to the marine littering and ghost fishing problematic. Considering the direct proportion between registered fishing vessels (Fiskeridirektoratet, 2017), amount of fishing activity and rate of FG loss upon deployment, a backcasting was conducted to estimate the fishing fleet's ALDFG contribution since 2007 (Fig. 7). Although dedicated efforts are made to retrieve ALDFGs from the ocean territory in Norway, an estimated annual influx of 308 tons remains unrecovered, piling up the stock in the ocean. Such retrospective estimation shows that approximately 4000 tons of plastic accumulated in the ocean since 2007 from Norwegian commercial fishing alone. Table S12 of SI presents the analysis steps followed for backcasting.

Buhl-Mortensen and Buhl-Mortensen (2017) conducted elaborate seabed mapping using 1778 video transects of Nordic oceans. They concluded the dominance of waste FGs in all marine landscapes across Norway, confirming the alarming quantities of accumulated FGs reported in this study. However, the estimate presented in Fig. 7 is still only partial as loads of ALDFG from international commercial fishing vessels fishing in Norwegian territory, leisure fishing boats and deliberate abandonment of FGs are not considered in current MFA study.

A 40-day long gear retrieval survey from the Directorate of Fisheries is an attempt to recover accumulated ALDFGs from fishing vessels throughout the year. A vessel equipped with recovery and FG location technology spans the length of the Norwegian coastline each summer. In 2016, the cleaning operation recovered around 20 tons of plastic FGs, 20-25 tons of metal wires, and several tons of marine animals entangled in fishing gears (Langedal, 2017), confirming the detrimental threats of the lost FGs fraction of overall marine litter. Cheap and abundantly deployed FG types such as gillnets, longlines, and associated ropes are the most significantly recovered fractions of ALDFG. Trawls and Danish seines are challenging to find and retrieve due to the presence of metal parts. These gear types sink into the ocean's depth, making them difficult to retrieve. Many of the sunken gears get entangled on coral reefs and rocky surfaces. Forcefully retrieving such FGs is usually avoided because it is likely to damage coral reefs or the marine ecosystem. Some of the lost FGs drift with the ocean currents to the coastline transferring the ALDFG load from the ocean to land. The lack of technology to locate lost FGs, coupled with adverse weather conditions, FGs drifting with ocean currents and the associated costs of retrieval operations significantly limit further improvements of ALDFG recovery. It is therefore essential to find a suitable alternative to manage and mitigate the accumulation of ALDFG in the ocean compartment alongside recovery and clean-up operations.

4.2. Sustainable management of FG resources

The mass flows estimation provided in the MFA analysis is raising

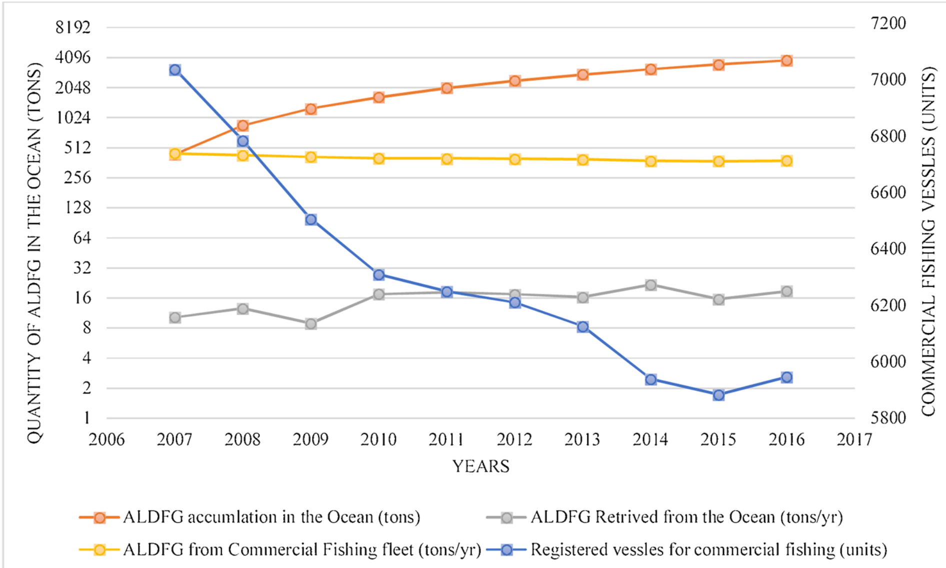

Fig. 7. Back-casting annual flow of plastic from lost FGs and accumulating in the ocean from 2007-2016.

awareness about the extent of plastics pollution from commercial fishing. More importantly, it also allows us to identify strategies for sustainable management of FG resources. Such strategies can prevent the detrimental effects of ALDFGs, and also generate circular economy opportunities through closing the FGs plastic loop. Table **S13** in the **SI** gives an overview of strategies considered relevant for the Norwegian commercial fishing sector modified after Deshpande and Aspen (2018). The proposed strategies are presented in relation to their application within FG lifecycle phases.

4.2.1. *Pre-use phase*

Gear marking or gear identification is considered a key strategy for responsible fishing and for controlling the ALDFG problem. This can enable fishers to minimize risks of losing FGs upon deployment, as well as aid authorities in improving collection and management of waste FGs. The Fisheries Department of the Food and Agricultural Organization (FAO) published a systemic guideline encouraging member states to incorporate gear marking in their policies. According to these guidelines, gear marking aids in providing an understanding of the location, scale and nature of FG in the water (FAO, 2016). Some of the proposed marking identifiers include electronic tagging, coded wire tags, barcoding, color-coded ropes, metal stamps or metal/steel tags incorporated into the FG. Information on gear location and ownership aids in estimating the position of the FG and in tracing the owners responsible for lost FGs.

Furthermore, the Norwegian government is considering Extended Producer Responsibility (EPR) as a strategy to minimize and prevent plastic pollution from FGs at a regional scale. Under the EPR, companies who produce, import or distribute FGs (the entire value chain up to the user of the equipment) will be responsible for the collection of the gear after use and for ensuring that it is properly recycled (Sundt et al., 2018). A feasibility assessment of the EPR scheme was conducted by the Norwegian Directorate of the Environment in 2018. It highlighted the need for in-depth understanding of the FG system's life cycle (flows and stocks) to aid in the selection of relevant mechanisms for the implementation of such regulation. This study may act as background evidence to support EPR policies before their implementation in Norway. A take back mechanism, a reward scheme for end-users to promote the collection of EOL FGs, is an example of an effective way to realize EPR at the regional scale. Introducing an Environmental Tax on the sale of fishing equipment is another proven strategy to internalize the costs of EOL collection and waste treatment in market prices. Stakeholder perception and market readiness must be assessed before implementing such strategy on a regional scale.

4.2.2. *Post-use handling and collection of FGs*

Currently, in Norway, marine litter caught during fishing can be handed in at the calling port. The costs associated with the reception of ship-generated waste are covered through the collection of a fee from all ships, irrespective of whether the ship-generated waste is delivered to the reception facility (EU DIRECTIVE, 2002). A dedicated EU Directive 2000/59/EC mandates all EEA member states to ensure availability of a Port Reception Facility (PRF) and a waste handling and management plan on all ports. PRFs are defined as 'any facility, which is fixed, floating or mobile and capable of receiving ship-generated waste or cargo residues'.

According to the recent judgment by the EFTA Court (2016), Norway has failed to fulfill the obligations under the EU directive, as only 1514 of 4443 registered ports and landing sites had showcased the availability of waste reception and a handling plan. A large number of landing sites without any dedicated waste management system led to the improper collection of fishing-related waste in the country. The absence of adequate facilities to collect ship-generated waste may result in illegal dumping, burning or stocking the waste on ports, and severely hinders the collection and treatment of waste FGs through adequate channels (EC, 2018a). Availability of PRFs is essential to ensure the reduction of marine plastic pollution from fishing and maritime activities. There is a need to develop a strategic plan to incorporate harmonized PRFs across Norway with the help of relevant stakeholders.

Strategies such as economic incentives and penalty schemes for fishing vessels may be considered to ensure the effective use of PRFs (Gilman, 2015). Additionally, stakeholder awareness campaigns may help to minimize the illegal dumping of marine litter on beaches and at sea. Additionally, training workshops for fishers to highlight best practices in handling FGs can prevent avoidable loss. Volunteering and deliberate clean-up campaigns are already proven mitigation measures for marine litter in Norway.

4.2.3. *Closing the loop for plastics from FGs*

To ensure the EOL management of plastics from FGs, it is essential to build the capacity and technology to extract value from waste based on circular economy principles. Currently, there exist numerous challenges in closing the loop for plastics from waste FGs. The EOL collection, segregation, capacity, and availability of recyclers are among the key concerns in realizing the economic benefits from material recovery.

In the Norwegian context, personal communication with waste managers revealed several challenges in handling waste FGs. One of the major challenges of WMFs is the lack of a best practice guide or harmonized technical expertise in cleaning and segregating waste FGs. Most EOL FGs are laden with rotten biomass, fish oil, and dirt. Since many WMFs lack the facility to clean such waste, the result is elevated rates of incineration or landfill within the waste fraction. Furthermore, an absence of industrial-scale recyclers' results in the exportation of the entire recyclable fraction out of Norway, thereby missing an opportunity to extract the optimum value out of locally produced waste FGs. Existing mechanical recycling technologies for PP and PE of waste FGs result in the formation of HDPE (high-density polyethylene) and LDPE (low-density polyethylene). These can be effectively used to replace virgin plastic polymers in products made by injection molding technology. Additionally, nylon polymers retain their properties through several recycling cycles, making nylon an economically attractive by-product to be recovered from waste FGs.

Although both chemical and mechanical technologies are available for closing the material loop, industrial-scale recycling of FGs faces many economic and operational challenges. Personal communication with the recyclers revealed that the transport and segregation of waste FGs from source to gate pose a significant economic burden to recyclers. The presence of metal wires in ropes and other parts of FGs makes it difficult to cut them into transportable pieces. These metallic parts cause wear and tear to the mechanical recycling units forcing frequent maintenance and repairs. Design and composition of modern FGs and lack of technical expertise at the waste collection facilities cumulatively hamper the maximum material recovery from waste FGs.

Finally, to make recovery of plastic sustainable, there is a need to create a harmonized network and building capacity of downstream actors involved in the EOL collection and management of FGs. Additionally, research on the eco-design of FGs must be emphasized to explore alternative FG material that allows efficient and profitable recycling without hampering the effectiveness. In its recent strategy, the EU invites innovation and business solutions across the member states to facilitate the transition towards a circular economy with a particular focus on marine plastic waste from FGs (EC, 2018b). Taking this into account, Norwegian plastic industries are currently tapping into opportunities by replacing fractions of their virgin polymers with recycled polymers from waste FGs. The amount of waste FGs available for recycling estimated in this study provides a piece of vital information for realizing an eco-industrial network between recyclers and plastic industries in the region.

4.3. Delimitations and Data quality

This static MFA study aims to provide a snapshot of all the activities taking place in the system life cycle of FGs. Inconsistency in the purchase flow is attributed to the variety of plastic content in FG types that differs across producers. Additionally, this study only includes major FG suppliers, which means that small-scale suppliers of gear to commercial and leisure fishers were excluded. Expert judgment was used to minimize this uncertainty and underestimation. The most significant data inconsistencies come from estimating average per unit weight of commercial FGs. Fishers often customize trawls, purse seines and Danish seines depending upon their needs, causing significant weight variations for these gear types. Furthermore, the average weights of FG types and expert judgment are used to calculate the plastic quantities in FGs collected in ocean and beach clean-up surveys. Contacted experts include the managers of clean-up surveys, and associated inconsistencies in the data may arise from simplifying the weights of certain gear types.

The uncertainty in survey response can be attributed to responders being speculative while answering specific questions where they lack knowledge. In the present study, the aim was to capture the annual repair, loss and disposal patterns of FGs. In the survey, some questions required fishers to summarize the past 10 to 20 years of fishing practices, which could lead to memory bias and unavoidable subjectivity. Additionally, statistical variations in responses from fishers are due to differences in fishing practices, target species, fishing grounds (coastal or deep-water), fishing quotas, and experience, among others. The dependency of this MFA on survey results is attributed to an overall lack of data on fishing practices, which highlights the need for improved monitoring practices of the Norwegian fishing fleet.

5. Conclusion

In this study, we present a system-wide analysis of the common Fishing Gears (FGs) used for commercial fishing, i.e., trawls, seines (Danish and Purse), longlines, gillnets, and traps and model the flows of plastics polymers (PP, PE, and Nylon) used as building blocks of advanced FGs. The MFA model aids in generating scientific evidence on quantities of plastic entering the ocean as ALDFG and EOL FGs available for recycling in Norway. The study further uncovers the state of plastic waste management from commercial fishing practices in Norway. The static MFA shows that irrespective of local land and ocean clean-up efforts, an estimated 300 tons of plastic is accumulating annually as ALDFG in the ocean ecosystem from the commercial fishing alone. Furthermore, the model reports that in 2017, around 55% of collected waste FGs are sent for further recycling out of Norway due to the absence of industrial recycling. In the wake of the recent Chinese ban on import of waste, there is a need to establish alternative ways to handle EOL FGs to avoid the accumulation of waste in the system.

These findings are already becoming a critical science and technology input for the Environmental and the Fishery Authorities of Norway aiding the formulation of policies to monitor and minimize the plastic pollution from the commercial fishing sector. Additionally, the results are likely to create a future paradigm for monitoring and implementation of the new European strategy for plastics and on port reception facilities (2018/012 COD). Finally, the reported annual quantities of plastic waste collected in the end-of-life stage is considered vital evidence for regional recyclers and waste managers that aim at closing the material loop from FG resources in Norway.

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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Appendix A. Supplementary data

Supplementary material related to this article can be found, in the online version, at doi:10.1016/j.rcrx.2019.100024.

References

Allesch, A., Brunner, P.H., 2017. Material Flow Analysis as a Tool to improve Waste Management Systems: The Case of Austria. Environmental Science & Technology 51, 540–551.

Baeta, F., Costa, M.J., Cabral, H., 2009. Trammel nets' ghost fishing off the Portuguese

central coast. Fisheries Research 98, 33–39.
Breen, P.A., 1987. Mortality of Dungeness Crabs Caused by Lost Traps in the Fraser River Estuary, British Columbia. North American Journal of Fisheries Management 7, 429–435.
Brown, J., Macfadyen, G., 2007. Ghost fishing in European waters: Impacts and management responses. Marine Policy 31, 488–504.
Browne, M.A., Chapman, M.G., Thompson, R.C., Amaral Zettler, L.A., Jambeck, J., Mallos, N.J., 2015. Spatial and Temporal Patterns of Stranded Intertidal Marine Debris: Is There a Picture of Global Change? Environmental Science & Technology 49, 7082–7094.
Browne, M.A., Galloway, T.S., Thompson, R.C., 2010. Spatial Patterns of Plastic Debris along Estuarine Shorelines. Environmental Science & Technology 44, 3404–3409.
Brunner, P.H., Rechberger, H., 2004. Practical handbook of material flow analysis. Springer.
Buhl-Mortensen, L., Buhl-Mortensen, P., 2017. Marine litter in the Nordic Seas: Distribution composition and abundance. Marine Pollution Bulletin 125, 260–270.
Chen, C.-L., 2015. Regulation and Management of Marine Litter. In: Bergmann, M., Gutow, L., Klages, M. (Eds.), Marine Anthropogenic Litter. Springer International Publishing, Cham.
Chen, Q., Reisser, J., Cunsolo, S., Kwadijk, C., Kotterman, M., Proietti, M., Slat, B., Ferrari, F.F., Schwarz, A., Levivier, A., Yin, D., Hollert, H., Koelmans, A.A., 2018. Pollutants in Plastics within the North Pacific Subtropical Gyre. Environmental Science & Technology 52, 446–456.
Chiappone, M., Dienes, H., Swanson, D.W., Miller, S.L., 2005. Impacts of lost fishing gear on coral reef sessile invertebrates in the Florida Keys National Marine Sanctuary. Biological Conservation 121, 221–230.
Chiappone, M., White, A., Swanson, D.W., Miller, S.L., 2002. Occurrence and biological impacts of fishing gear and other marine debris in the Florida Keys. Marine Pollution Bulletin 44, 597–604.
Cho, D.-O., 2011. Removing derelict fishing gear from the deep seabed of the East Sea. Marine Policy 35, 610–614.
Court, E., 2016. EFTA Surveillance Authority v The Kingdom of Norway (Failure by an EFTA State to fulfill its obligations — Directive 2000/59/EC on port reception facilities for ship-generated waste and cargo residues). European Free Trade Association (EFTA). Case E-35/15 ed, Luxembourg Official Journal of the European Union.
Derraik, J.G., 2002. The pollution of the marine environment by plastic debris: a review. Marine pollution bulletin 44, 842–852.
Deshpande, P.C., Aspen, D.M., 2018. A Framework to Conceptualize Sustainable Development Goals for Fishing Gear Resource Management. In: Leal Filho, W. (Ed.), Handbook of Sustainability Science and Research. Springer International Publishing, Cham.
Deshpande, P.C., Brattebø, H., Fet, A.M., 2019. A method to extract fishers' knowledge (FK) to generate evidence for sustainable management of fishing gears. MethodsX 6, 1044–1053.
Directive, H.A.T, 2002. DIRECTIVE 2002/84/EC OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL.
EC, 2018a. DIRECTIVE OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL on port reception facilities for the delivery of waste from ships, repealing Directive 2000/59/EC and amending Directive 2009/16/EC and Directive 2010/65/EU. European Commission, Directorate-General for Mobility and Transport., Strasbourg.
EC, 2018b. In: European Commission, E (Ed.), Proposal for a Directive of The European Parliament and of The Council on the reduction of the impact of certain plastic products on the environment. Brussels.
EU, 2014. In: COMMISSION, E (Ed.), Towards a circular economy: A zero waste programme for Europe. COM (2014).
Falk-Andersson, J., Berkhout, B.W., Abate, T.G., 2019. Citizen science for better management: Lessons learned from three Norwegian beach litter data sets. Marine Pollution Bulletin 138, 364–375.
FAO, 2016. Report of the Expert Consultation on The Marking of Fishing Gear. In: Nations, F. A. A. O. O. T. U (Ed.), FAO Fisheries and Aquaculture Report. Food and Agriculture Organization of The United Nations, Rome, Italy.
Fischer, J., Jorgensen, J., Josupeit, H., Kalikoski, D., Lucas, C.M., 2015. Fishers' knowledge and the ecosystem approach to fisheries: applications, experiences and lessons in Latin America. FAO Fisheries and Aquaculture Technical Paper, I.
Fiskeridirektoratet, 2017. In: Fisheries, N. D. O (Ed.), Norwegian fishing vessels, fishermen and licenses. Statistikkavdelingen.
Foekema, E.M., De Gruijter, C., Mergia, M.T., Van Franeker, J.A., Murk, A.J., Koelmans, A.A., 2013. Plastic in North Sea Fish. Environmental Science & Technology 47, 8818–8824.
Galgani, F., Fleet, D., Van Franeker, J., Katsanevakis, S., Maes, T., Mouat, J., Oosterbaan, L., Poitou, I., Hanke, G., Thompson, R., 2010. Marine Strategy Framework directive-Task Group 10 Report marine litter do not cause harm to the coastal and marine environment. Report on the identification of descriptors for the Good Environmental Status of European Seas regarding marine litter under the Marine Strategy Framework Directive. Office for Official Publications of the European Communities.
Gilman, E., 2015. Status of international monitoring and management of abandoned, lost and discarded fishing gear and ghost fishing. Marine Policy 60, 225–239.
Graeme Macfadyen, T.H.A.R.C., 2009. Abandoned, lost or otherwise discarded fishing gear. UNEP Regional Seas Reports and Studies No.185. UNITED NATIONS ENVIRONMENT PROGRAMME FOOD AND AGRICULTURE ORGANIZATION OF THE UNITED NATIONS, Rome.
Habib, K., Schibye, P.K., Vestbø, A.P., Dall, O., Wenzel, H., 2014. Material Flow Analysis of NdFeB Magnets for Denmark: A Comprehensive Waste Flow Sampling and Analysis Approach. Environmental Science & Technology 48, 12229–12237.
Hartviksen, M.K., 2017. Sluttrapport 2017 Strand og kystrydding av marint avfall i Lofoten. Lofoten Avfallsselskap IKS.
Hind, E.J., 2014. A review of the past, the present, and the future of fishers' knowledge research: A challenge to established fisheries science. ICES Journal of Marine Science 72, 341–358.
Hong, S., Lee, J., Lim, S., 2017. Navigational threats by derelict fishing gear to navy ships in the Korean seas. Marine Pollution Bulletin 119, 100–105.
Humborstad, O.-B., Løkkeborg, S., Hareide, N.-R., Furevik, D.M., 2003. Catches of Greenland halibut (Reinhardtius hippoglossoides) in deepwater ghost-fishing gillnets on the Norwegian continental slope. Fisheries Research 64, 163–170.
Jacob, M., 2016. Strandrydderapporten 2016 (Beach Cleaning Report 2016). Hold Norge Rent, Oslo.
Jambeck, J.R., Geyer, R., Wilcox, C., Siegler, T.R., Perryman, M., Andrady, A., Narayan, R., Law, K.L., 2015. Plastic waste inputs from land into the ocean. Science 347, 768–771.
Johannes, R.E., 1998. The case for data-less marine resource management: Examples from tropical nearshore finfisheries. Trends in Ecology and Evolution 13, 243–246.
Johnsen, H.R., 2017. In: Miljødirektoratet (Ed.), «Fishing For Litter» as a measure against marine litter in Norway. SALT Lofoten AS (SALT) ved Vilma Havas og Hilde Rødås Johnsen, Oslo, Norway.
Koelmans, A.A., Besseling, E., Foekema, E., Kooi, M., Mintenig, S., Ossendorp, B.C., Redondo-Hasselerharm, P.E., Verschoor, A., Van Wezel, A.P., Scheffer, M., 2017. Risks of Plastic Debris: Unravelling Fact, Opinion, Perception, and Belief. Environmental Science & Technology 51, 11513–11519.
Laist, D.W., 1997. Impacts of marine debris: entanglement of marine life in marine debris including a comprehensive list of species with entanglement and ingestion records. Marine Debris. Springer.
Laner, D., Rechberger, H., Astrup, T., 2014. Systematic Evaluation of Uncertainty in Material Flow Analysis. Journal of Industrial Ecology 18, 859–870.
Langedal, G., 2011. Opprenskning av tapte fiskeredskap 2011. Norway. .
Langedal, G., 2017. Opprensking av tapte fiskeredskap 2017. Fiskeridirektoratet, Norway.
Lebreton, L., Slat, B., Ferrari, F., Sainte-Rose, B., Aitken, J., Marthouse, R., Hajbane, S., Cunsolo, S., Schwarz, A., Levivier, A., 2018. Evidence that the Great Pacific Garbage Patch is rapidly accumulating plastic. Scientific reports 8, 4666.
Macfadyen, G., Huntington, T., Cappell, R., 2009. Abandoned, lost or otherwise discarded fishing gear. Food and Agriculture Organization of the United Nations (FAO).
Macmullen, P., 2002. Fantared 2, a study to identify, quantify and ameliorate the impacts of static gear lost at sea. ICES Council Meeting Documents.
Moore, C.J., 2008. Synthetic polymers in the marine environment: A rapidly increasing, long-term threat. Environmental Research 108, 131–139.
Muus, B.J., Nielsen, J.G., 1999. Sea fish. Scandinavian Fishing Year Book.
Phillips, R.A., Ridley, C., Reid, K., Pugh, P.J.A., Tuck, G.N., Harrison, N., 2010. Ingestion of fishing gear and entanglements of seabirds: Monitoring and implications for management. Biological Conservation 143, 501–512.
Richardson, K., Gunn, R., Wilcox, C., Hardesty, B.D., 2018. Understanding causes of gear loss provides a sound basis for fisheries management. Marine Policy.
Schneider, F., Parsons, S., Clift, S., Stolte, A., Mcmanus, M.C., 2018. Collected marine litter — A growing waste challenge. Marine Pollution Bulletin 128, 162–174.
Stelfox, M., Hudgins, J., Sweet, M., 2016. A review of ghost gear entanglement amongst marine mammals, reptiles and elasmobranchs. Marine Pollution Bulletin 111, 6–17.
Sundt, P., Briedis, R., Skogesal, O., Standal, E., Johnsen, H.R., Schulze, P.E., 2018. In: MILJØDIREKTORATET (Ed.), Underlag for å utrede produsentansvarsordning for fiskeri og akvakulturnæringen, Norge.
Van Eygen, E., Feketitsch, J., Laner, D., Rechberger, H., Fellner, J., 2017. Comprehensive analysis and quantification of national plastic flows: The case of Austria. Resources, Conservation and Recycling 117, 183–194.
Wilcox, C., Mallos, N.J., Leonard, G.H., Rodriguez, A., Hardesty, B.D., 2016. Using expert elicitation to estimate the impacts of plastic pollution on marine wildlife. Marine Policy 65, 107–114.
Yoshikawa, T., Asoh, K., 2004. Entanglement of monofilament fishing lines and coral death. Biological Conservation 117, 557–560.