Sunniva Andrine Hellesund

Quantifying entanglement impacts from lost fishing gear

A life cycle assessment of a gillnet fishery in Tromsø, Norway

Master's thesis in Industrial Ecology
Supervisor: Francesca Verones
Co-supervisor: Marthe Alnes Høiberg
June 2022

Master's thesis

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Kunnskap for en bedre verden

Abstract

Plastics are continuing to accumulate in the ocean due to mismanaged waste or directly disposal or loss in the ocean. Plastic in the marine environment is known for causing impacts such as entanglement and ingestion due to marine species interacting with debris. Even though the consequences of plastic debris have received increased attention, sustainability tools such as life cycle assessment (LCA) does not yet account for plastic as a pollutant. As such, there is a methodological gap within the LCA framework. This thesis contributes to tackle this methodological gap by accounting for the environmental impacts associated with lost fishing gear, specifically gillnets, in Tromsø in northern Norway by conducting a simplified LCA. For this purpose, the LCA software Brightway2 which is based on the programming language Python was used. The ReCiPe 2008 method at an endpoint level with a hierarchist perspective was applied as the impact assessment method. Further, the thesis aims at testing the newly developed characterization factor (CF) for entanglement as a potential impact pathway to loss of marine biodiversity by adjusting the loss rate of gillnets. The main findings of the simplified LCA study were that the number of potentially lost species was mainly due to global warming and the production and use of fuel for the fishing vessel, whereas entanglement due to lost gillnet contributed the least to species loss. The test of the CF for entanglement showed that an increase in the loss rate led to species loss of four times higher than the initial result. Even though entanglement contributed the least to overall impacts in this study, the result indicate that the leakage of gillnets leads to species loss. As such, the relevance of including entanglement of marine species in macroplastic in future LCA studies is significant.

Sammendrag

Plast fortsetter å akkumulere i havet på grunn av mangelfulle avfallshåndteringssystemer og direkte deponering eller tap i havet. Plast i det marine miljøet er kjent for å forårsake påvirkninger som innvikling og inntak på grunn av at marine arter samhandler med avfall. Selv om konsekvensene av plastsøppel har fått økt oppmerksomhet, tar ikke bærekraftsverktøy som livssyklusanalyse (LCA) foreløpig hensyn til plastavfall som et utslipp. Som sådan er det et metodisk hull innenfor LCA-rammeverket. Denne oppgaven bidrar til å håndtere dette metodiske hullet ved å redegjøre for miljøpåvirkningene knyttet til tapte fiskeredskaper, nærmere bestemt garn, i Tromsø i Nord-Norge ved å gjennomføre en forenklet LCA. Til dette formålet ble LCA-programvaren Brightway2 som er basert på programmeringsspråket Python brukt. ReCiPe 2008-metoden på endepunkt med et hierarkistisk perspektiv ble brukt som metode i karakteriseringsfasen. Videre har oppgaven som mål å teste den nyutviklede CF for innvikling som en mulig påvirkningsvei til tap av biologisk mangfold ved å justere tapsraten for garn. Hovedfunnene i den forenklede LCA-studien var at antallet mulig tapte arter hovedsakelig skyldtes global oppvarming og produksjon og bruk av drivstoff til fiskefartøyet, mens innvikling på grunn av tapt garn bidro minst til artstapet. Testen av CF for innvikling viste at en økning i tapsraten førte til artstap fire ganger høyere enn det opprinnelige resultatet. Selv om innvikling i garn bidro minst til de totale effektene i denne studien, indikerer resultatet at tap av garn fører til artstap. Derfor er relevansen av å inkludere sammenfiltring av marine arter i makroplast i fremtidige LCA-studier betydelig.

Acknowledgements

This master thesis is linked to the ATLANTIS project focusing on quantifying the effects of plastic debris on marine species and the inclusion of this within life cycle impact assessment (LCIA). I am grateful for and would like to thank my supervisor Professor Francesca Verones and co-supervisor Marthe Alnes Høiberg for their helpful guidance throughout the work of this thesis. I also want to thank my parents and sisters for their encouragement and support. Furthermore, I would like to thank Anna Eide Lunde for all help and proof reading. Lastly, a big thank you to my fellow students in the Industrial Ecology program at NTNU.

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Abbreviations

AB	Activity Browser
ALDFG	Abandoned, lost, or otherwise discarded fishing gear
AoP	Area of Protection
Brightway2	Brightway version 2
CF	Characterization factor
CH4	Methane
CO	Carbon monoxide
CO2	Carbon dioxide
FU	Functional unit
LCA	Life cycle assessment
LCI	Life cycle inventory
LCIA	Life cycle impact assessment
LDPE	Light density polyethylene
MFA	Material flow analysis
NMVOC	Non-methane volatile organic compounds
NOx	Nitric oxide
PA	Polyamide
PDF	Potentially disappeared fraction of species
PE	Polyethylene
PET	Polyester
PLP	Plastic leak project
PP	Polypropylene
SO2	Sulphur dioxide
SSD	Species sensitivity distribution

1 Introduction

Marine litter, and especially plastic is considered a major threat for the marine ecosystem and for human health (Kühn & van Franeker, 2020), because of its unique properties such as persistence and durability in the marine environment (Jambeck et al., 2015). The continuous production and consumption of plastics as well as poor waste management systems can lead to plastic entering the natural environment (Jambeck et al., 2015; Peano et al., 2020). Mismanaged plastic waste can accumulate from landfills or be discharged directly into rivers, coastlines, and oceans, and become plastic debris. Additionally, due to weathering, plastic debris undergoes fragmentation and degradation into smaller pieces and particles (Jambeck et al., 2015). These occurrences are called plastic leakage.

The attention surrounding the negative effects of plastic pollution have increased, the consumption however continues. About 8.3 billion tons of plastic have been produced since the beginning of plastic production in the 1950's (United Nations Environment Programme, 2018). At the same time, plastic waste enters the ocean with an estimated inflow of 4.8 to 12.7 million tons per year (Jambeck et al., 2015). Once in the ocean, plastic waste forms garbage patches (Lebreton et al., 2018), and impacts marine species and ecosystems (Kühn et al., 2015).

The sustainable development goal 14 emphasizes the importance of taking care of the oceans, seas and marine resources (United Nations, n.d.). In terms of marine ecosystems and pollution to the oceans, it has become increasingly important to focus on reducing plastic use as well as obtaining well-functioning waste management systems. Therefore, reducing the production of virgin plastic is necessary in order to prevent plastic accumulation in the ocean (Bergmann et al., 2022). The information and data on marine debris is to date inadequate which limits reaching the sustainable development goal number 14, i.e., life below water (Gilman et al., 2021b).

Among the most visible impacts of plastic pollution is entanglement (Kühn et al., 2015). Entanglement can be described as animals becoming trapped in openings of plastic items (Laist, 1987). Common entangling items are plastic packaging bands and straps (Allyn & Scordino, 2020; Boren et al., 2006) and fishing gear such as nets and lines (Boren et al., 2006; Greg Hofmeyr et al., 2006; Wilcox et al., 2013). Entanglement can lead to reduced mobility, injuries and mortality (Kühn et al., 2015). Marine animals interact with plastic debris due to curiosity towards the item, to seek entangled pray, confuse it with food, or to use it as shelter or a nesting item (Senko et al., 2020). It is important to increase the understanding of the plastic leakage origins, in addition to why the leakage occurs to reduce the chance of plastic waste becoming debris and impacting marine animals through entanglement (Boucher, Zgola, et al., 2020).

Abandoned, lost, or otherwise discarded fishing gear (ALDFG) is considered a significant cause of mortality for marine animals (Senko et al., 2020). Fishing gear is usually made of plastic such as nylon, polypropylene, and polyethylene which has long durability in the marine environment (Deshpande et al., 2020). In addition, fishing gear is designed to target fish and has the ability to continue to catch fish even after its use phase, called "ghost fishing", when the gear is lost, abandoned or discarded (Deshpande et al., 2020; Macfadyen & Huntington, 2009). Within the fishing industry there are major challenges regarding leakage of fishing gear to the ocean potentially generating negative impacts for marine ecosystems (Loubet et al., 2022). A life cycle approach to evaluate the environmental performance of lost fishing gear can contribute to identify hotspots for losses along the value chain and enable systemic reduction targets.

Life cycle assessment (LCA) is a tool for assessing the environmental impacts occurring throughout the life cycle of a product or an activity (Hauschild et al., 2017). This tool can be applied for different studies depending on the goal and scope and can be used for identifying trade-offs and comparing alternative solutions (Woods et al., 2016). Compared to terrestrial and freshwater ecosystems, the marine environment is underrepresented within life cycle impact assessment (LCIA). To date, there are only two impact categories for the marine environment covered on a global scale: marine ecotoxicity and marine eutrophication. Plastic can be understood as an emission flow or pollutant affecting ecosystems and/or human health (Boucher, Zgola, et al., 2020), similar to for instance carbon dioxide (CO_2) impacting ecosystems and human health through global warming. However, this is a gap within LCA methodologies where only effects from resource depletion, energy consumption, and emissions related to for instance production of the plastic are accounted for in life cycle inventory (LCI) databases (Boucher, Billard, et al., 2020). There is a need for considering plastic debris as a pollutant, as well as develop characterization factors (CF) for the assessment of impacts on ecosystems within the LCIA framework (Boucher, Billard, et al., 2020).

The aim of this thesis is to account for the impacts of lost fishing gear associated with cod fishing using gillnets in Norway and test the newly developed CF for entanglement as a potential impact pathway to biodiversity loss. The CF is tested by altering the loss rate to specifically a global estimate as well as an additional estimate for Norway. The choice of gillnets is based on the project thesis, where entanglement studies and clean-up reports were investigated to identify the most common plastic items in the marine environment as well as the most frequent items known for causing entanglement effects. As a result, fishing gear and more specifically gillnets, are shown to be one of the most frequent entangling items. To be able to account for the potential impacts from the gillnet fishery, the sustainability assessment method, LCA, was the basis for the methodology using the Python based software Brightway version 2 (Brightway2).

2 Background

2.1 Plastic in the marine environment

The production of plastic is rapidly growing, as it has been since the 1950's (Geyer et al., 2017). The Plastic Leak Project (PLP) estimate that 415 million tons of plastic is produced every year (Peano et al., 2020). Plastics are commonly used in a wide range of products consisting of mainly polymers such as polypropylene (PP), polyethylene (PE), as well as polyester (PET) and polyamide (PA) also known as nylon, with additives to amplify the product's properties (Geyer et al., 2017). Moreover, plastics are widely used in packaging for food and beverages, chemicals and cosmetics (Ganesh et al., 2020), but also used in construction, transportation, textiles, electronic and electrical equipment (Geyer, 2020). Since plastics are not biodegradable and inexpensive to produce, they are likely to end up in the natural environment through accumulating directly or in landfills (Laist, 1987). It is widely cited that plastic is present in the marine environment, and considered a concern due to its significant impacts on marine ecosystems and animals (Ryberg et al., 2019).

Current values on global plastic leakage are ranging from 4.8 to 12.7 million tons annually (Boucher, Billard, et al., 2020; Jambeck et al., 2015; Peano et al., 2020). The PLP estimated that 11 million tons of plastic leaks to the natural environment every year, releasing 3% of the annual plastic production (Figure 1) (Peano et al., 2020). Plastic leakage to the environment can occur in every step along the value chain, from production, use and end-of-life (Ryberg et al., 2019). Based on their size, plastic is divided into nano-, micro-, macro-, and megaplastics (Ganesh et al., 2020). In connection to this, plastic smaller than 5 mm is defined as micro- and nanoplastic, whereas plastic larger than 5 mm is referred to as macroplastic (Peano et al., 2020). Furthermore, macroplastics enter the marine environment mainly in their end-of-life phase, either through mismanaged or improper disposal of plastic waste, or through lost or discarded plastic directly to the ocean, for instance lost fishing nets (Boucher, Billard, et al., 2020; Peano et al., 2020). The leakage of microplastic to the natural environment is less visible than for macroplastics due to its size, and can originate from particles from cosmetic products or abrasion of for instance paint or tires (Boucher, Billard, et al., 2020; Peano et al., 2020). Only macroplastics are considered in this thesis, given that the overall topic is entanglement in plastic debris where most events occur in macroplastic.

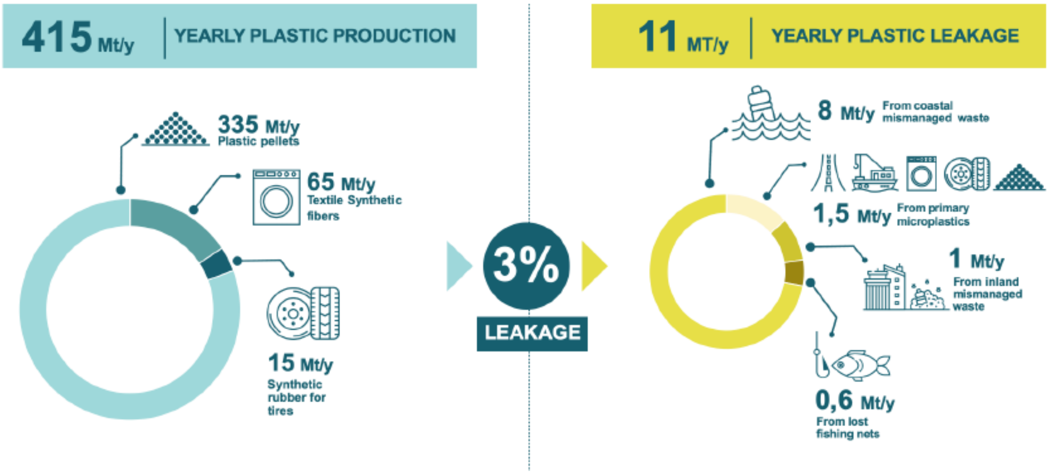

Figure 1 - Annual plastic production and leakage by source. Most recent estimates. Source: (Peano et al., 2020).

When plastic waste enters the environment, depending on their shape and size, it can be transported by winds or currents either to other environmental compartments, for example to beaches, or to areas where plastic debris form patches, often referred to as "garbage patches" (Ganesh et al., 2020; Lebreton et al., 2018). There are five garbage patches in the world located in the Indian Ocean, Atlantic Ocean, and Pacific Ocean (NOAA, n.d.-b). These "garbage patches" function as hotspots for marine debris (Lebreton et al., 2018), and can potentially impact marine species through ingestion, entanglement, and smothering (Kühn et al., 2015). Depending on several factors, for example size, plastic waste will have a release rate once it enters the environment, meaning the fraction of lost or discarded waste that reaches the natural environment (Peano et al., 2020). The release rate can be divided into initial release, referring to the environmental compartment the plastic first reaches after being discarded, and final release referring to the environmental compartment the plastic ends up in after redistribution (Maga et al., 2021; Peano et al., 2020).

Plastic debris can come from either land- or ocean-based sources (Macfadyen & Huntington, 2009). The land-based sources can be e.g., plastic bags, plastic bottles, food containers, straws, or wrappers (Morales-Caselles et al., 2021). These types of packaging items are often lightweight single-use plastic which are cheap to produce, and as a consequence are likely to be discarded in the environment due to improper disposal (Laist, 1987). Packaging items are commonly found in many of the aquatic compartments; along beaches, rivers, the seabed and within shorelines

(Figure 2) (Morales-Caselles et al., 2021). Although the sea-based sources such as abandoned, lost, or discarded fishing gear (ALDFG) represent a smaller amount of plastic debris in the marine environment as shown in Figure 2 (Jambeck et al., 2015; Morales-Caselles et al., 2021), it has the potential of causing considerable harm to marine species due to its properties and design (Kuczenski et al., 2022). ALDFG include derelict fishing gear such as nets, ropes, lines, pots, and traps (Macfadyen & Huntington, 2009). Both plastic packaging items and fishing gear, especially nets, have shown to be the most dangerous to marine animals (Laist, 1987). Therefore, the focus of this thesis is specifically fishing gear.

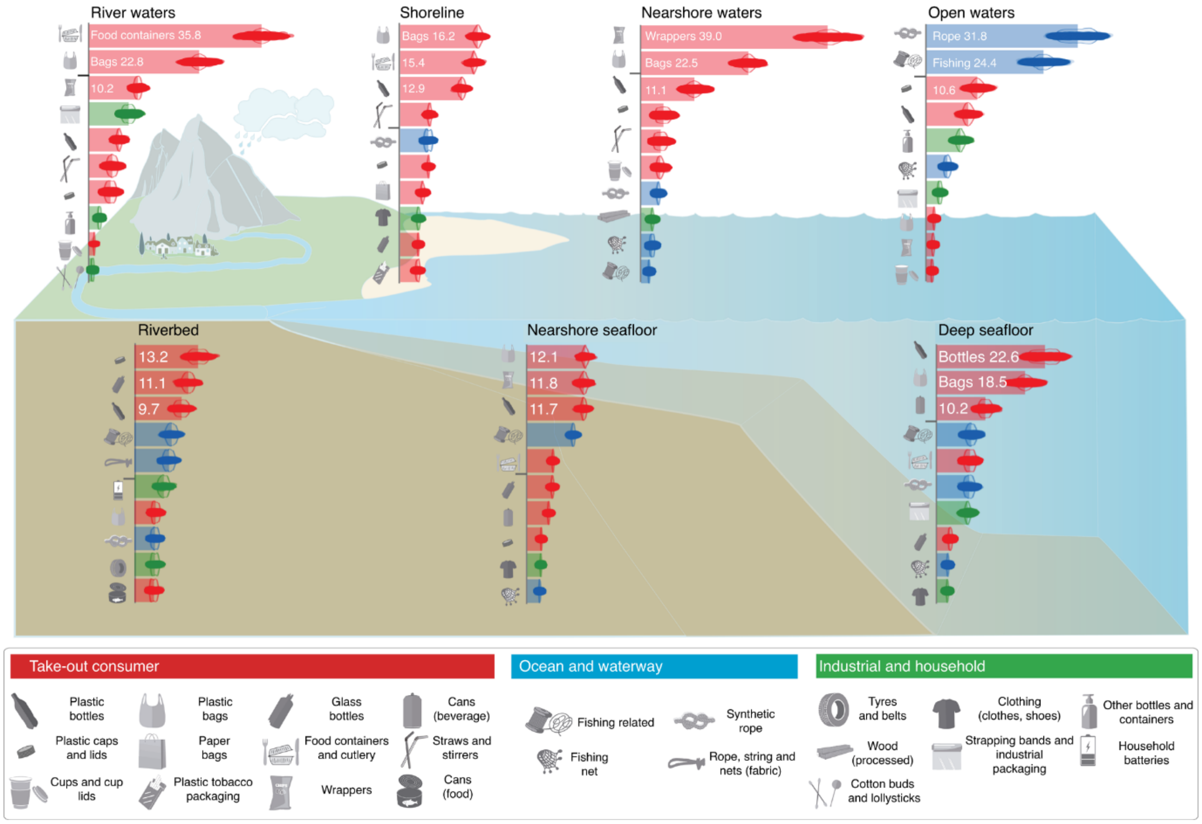

Figure 2 - Common litter items in aquatic environments. The bar colors refer to the litter's origin: red color refers to take-out consumer products, blue is ocean-based litter, and green is industrial and household items. Including all litter items, not only plastic. The bars reflect the mean percentages for each environment (each environment adds up to 100%). The darker-colored areas reflect the uncertainty of the percentage estimate. Source: (Morales-Caselles et al., 2021).

2.2 Entanglement of marine species in plastic debris

Threats to marine life from plastic debris are well known and occurring all over the world. Entanglement is an impact pathway where marine animals interact with plastic debris and become trapped in loops and openings of the item (Laist, 1997). Common entangling items are plastic bags, packaging bands and straps, ropes, and fishing nets and lines, which can cause significant injuries, reduced mobility or mortality (Kühn et al., 2015; Laist, 1987). Several species have been recorded entangled in marine debris, and to date there are 344 species documented (Kühn et al., 2015). These species range from whales and seals to birds and turtles. Pinnipeds (seals) are commonly documented in literature, often entangled in derelict fishing gear (Curtis et al., 2021; Jepsen & de Bruyn, 2019). Nevertheless, there is no common correlation in entanglement studies whether some species interact more with fishing gear rather than with other plastic debris (Curtis et al., 2021). Moreover, since winds and currents transport the debris to a vast range of geographic areas, entanglement events can happen all over the world. In addition, an entangled animal which has died is likely to be eaten by predators or to sink and decompose (Laist, 1987) and thus will not be registered as having been entangled. Since only individuals are reported, it can be difficult to conclude that an entire species population is affected by entanglement (Laist, 1987; Wilcox et al., 2016). Nevertheless, entanglement constitutes a danger to marine animals and potential loss of biodiversity (Høiberg et al., 2022). Furthermore, the lack of quantitative assessments regarding the impacts of entanglement, in addition to the difficulties with recording marine animals and potential injuries and mortality, constitutes a large knowledge gap (Høiberg et al., 2022).

ALDFG is especially hazardous for marine animals as these items are designed to capture fish (Deshpande et al., 2020). Additionally, the term “ghost fishing” has been used referring to the ability of fishing gear to continue to entangle and kill marine animals after it is lost, abandoned, or discarded of (Gilman et al., 2016). During the last decades there has been a transition towards using synthetic materials for the production of fishing gear, which are more durable in the marine environment (Deshpande & Haskins, 2021). Additionally, as fishing activities have been rapidly growing and the amount and distribution of ALDFG have increased, the gear’s ability to reduce fish stocks as a consequence of ghost fishing, as well as threaten marine animals through entanglement have risen (Deshpande & Haskins, 2021). It is important to note that there is a risk of entanglement while the fishing gear is active, in addition to the risk if the gear is accidentally lost or deliberately abandoned. Fishers may encounter unintended catch, which is often referred to as “bycatch” (NOAA, n.d.-a). This can be non-targeted fish or protected species such as turtles and marine mammals. Bycatch is often discarded by the fishers, left dead or significantly injured, which in turn can lead to biodiversity loss (NOAA, n.d.-a).

The type of fishing gear shown to pose the highest risk to marine species is gillnets, both drift gillnet and set and fixed gillnet (Gilman et al., 2021a). Gillnets are fishing gear aimed at catching fish by entangling them (Figure 3) (NOAA, 2021). They are commonly used for targeting both demersal and pelagic fish species such as cod, herring, and mackerel (NOAA, 2021). Additionally, gillnets are cheap to produce, and efficient and easy to use. They are the type of fishing gear most frequently used by the conventional fishing fleet in Norway, i.e. vessels smaller than 27,9 meters in length (Standal et al., 2020). Even though Norway has well-functioning systems for locating gillnet deployments, a considerable amount of gillnets are lost to the ocean every year (Standal et al., 2020). In terms of official clean-ups, the Norwegian Directorate of Fisheries estimated that around 100 tons of lost and discarded fishing gear were removed from the seabed between Ålesund and Svalbard in Norway in 2020 (Directorate of Fisheries, 2020b). Deshpande et al. (2020) estimated through conducting a material flow analysis (MFA) that 55 tons of plastic originating from lost or discarded fishing gear is retrieved every year. This was estimated based on numbers from the yearly gear retrieval conducted by the Norwegian Directorate of Fisheries and a project called Fishing for Litter focusing on removing marine litter in Norway and increase awareness in terms of littering in the fishing industry (Havas & Johnsen, 2017).

Regarding fishing gear lost to the ocean in Norway, Deshpande et al. (2020) determined the loss rate of six different fishing gears within Norway, one of them set gillnets which are nets fixed to the seabed with anchors and a lead rope aimed at targeting demersal fish species such as cod. The loss rate of gillnets was estimated to be between 1% and 2% (Deshpande et al., 2020). On a global scale gillnets appear to have a higher loss rate, estimated to be around 5.8% (Richardson et al., 2019). One reason for this may be that in the Nordic countries there are a small number of fishing ports which are large, whereas other countries have several small ports (The Nordic

Council of Ministers, 2020). A second reason are the availability of a good road network and sufficient waste management systems in Nordic countries. For example, Denmark is characterized with few fishing ports as well as good waste handling systems, as opposed to Greenland which has many fishing ports, often small, where most of the waste ends up in landfills which accumulates in the ocean (The Nordic Council of Ministers, 2020). Additionally, in Norway there are restrains on dumping fishing gear into the sea and the majority of commercial fishers need to document when and where the gear is deployed and taken on board again (The Nordic Council of Ministers, 2020). Even though these restrictions exist, there are still challenges with obtaining good reporting systems in Norway and in other countries due to recreational and international fishing vessels not entailing these restrictions (The Nordic Council of Ministers, 2020).

In terms of entanglement in gillnets, several publications report of entanglement events in derelict fishing nets, affecting fur seals, sea lions, and birds at a global scale (Greg Hofmeyr et al., 2006; Page et al., 2004; Raum-Suryan et al., 2009; Ryan, 2018; Waluda & Staniland, 2013; Wilcox et al., 2013). The structure of the material can determine the fate and effect of a plastic item in the ocean (Loubet et al., 2022), and since fishing gear, such as nets, are designed for capturing fish by entangling them, ALDFG is especially hazardous for marine animals (Deshpande et al., 2020).

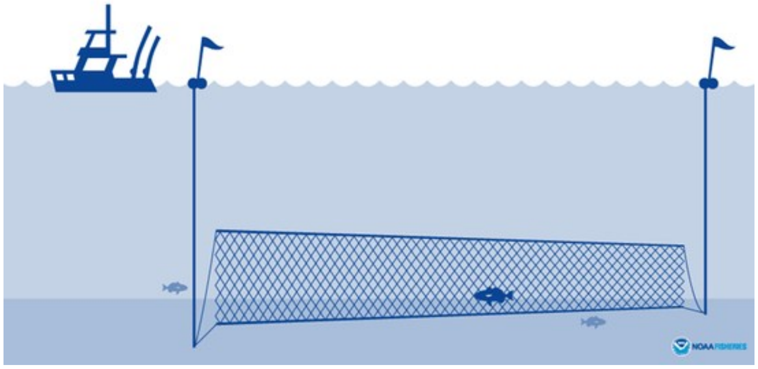

Figure 3 - Figure shows a gillnet fixed to the seabed and includes buoys, the net, float rope at the top of the net, and lead rope at the bottom of the net. Source: (NOAA, 2021).

2.3 Accounting for plastic debris in the LCA framework

Life cycle assessment (LCA) is a method for quantifying and evaluating environmental impacts of products or activities by accounting for the inputs and outputs of a system throughout its life cycle (Hauschild et al., 2017). The method is well known and commonly used for comparing alternatives based on the environmental performance, identify trade-offs, and enable reduction targets (Hauschild et al., 2017; Woods et al., 2016). According to the LCA framework, an LCA is split into four steps: goal and scope definition, life cycle inventory (LCI), life cycle impact assessment (LCIA), and interpretation of the results (ISO, 2006). The functional unit and system boundary is assessed within the goal and scope definition, followed by the data collection in the LCI (ISO, 2006). In the LCIA stage, emissions are converted to a set of environmental impact scores, such as for instance climate change or marine ecotoxicity (Huijbregts et al., 2017). To translate the scores to impact categories, characterization factors (CF) are used. Characterization factors are given in impact per unit of the chosen stressor (Huijbregts et al., 2017). These CFs can be used at the midpoint level, for example global warming potential or land use, or at endpoint level which include three categories or Areas of Protection (AoP): ecosystem quality, human health, and resource scarcity (Huijbregts et al., 2017). Moreover, regionalization within LCA refers to the fact that some LCI data and impact categories in LCIA have different impacts based on the region they occur in (Pfister et al., 2020).

In terms of plastic debris and its impact on marine species, the LCA framework does not yet address this potential pathway to loss of marine biodiversity. No life cycle inventory databases includes the emission flows of plastic leakage yet, which coincides with the fact that few LCA studies incorporate the exchange between plastic and the natural environment in their inventory modelling (Boulay et al., 2021). The lack of sufficient data on plastic as a pollutant also limits the development of life cycle impact assessment methodologies (Maga et al., 2021).

Within the life cycle impact assessment framework there are only two impact categories relevant to the marine environment: marine ecotoxicity and marine eutrophication. Initiatives have been raised to tackle this methodological gap within the LCA framework. The MarILCA (Marine Impacts in LCA) network focuses on impact assessment and the development of a method for including first and foremost plastic debris in LCIA (Boulay et al., 2021). The ATLANTIS project is developing a model for the quantification of impacts from plastic pollution and invasive species on marine ecology (Atlantis, 2020). Additionally, the Plastic Leak Project (PLP) is addressing the methodological gap by focusing on the inventory and emission calculations (Maga et al., 2021; Peano et al., 2020). With regard to entanglement in macroplastic, a preliminary method has been developed (Woods et al., 2019), and the first part of an improved effect factor (EF) have been published as well (Høiberg et al., 2022).

A recent study assessed the life cycle inventory of different plastic losses along the value chain of several fishing gears in France (Loubet et al., 2022). They emphasize the need to develop the work and include the inventory of plastic losses to potential effects in impact assessment (Loubet et al., 2022). Regarding the aspect of plastic litter, some LCA studies have been conducted (Civancik-Uslu et al., 2019; Zanghelini et al., 2020), however, neglecting impacts that may affect marine species, due to lack of available methodology.

Accounting for plastic debris in an LCA gives rise to additional requirements related to the data inventory and impact assessment. The rate at which the fishing gear leaks to the ocean needs to be established, and where the origin of the plastic was, needs to be defined (Peano et al., 2020). The loss rate depends on the type of gear, location, weather, and whether there is an incentive to prevent loss or retrieve the gear if lost. Regarding the impact assessment phase, a characterization factor for the specific impact pathway is needed, taking into account a fate and effect factor. There is need for improving the LCA framework to incorporate plastic debris as this is a major concern in terms of biodiversity loss and ecosystem damage.

3 Materials and method

3.1 Goal and scope definition

The goal of this LCA study is to quantify and evaluate the environmental impacts caused by fishing activity in Norway with a focus on cod caught with gillnets. The choice of gillnets is based on the preceding work in the project thesis where literature indicated that nets from the fishery industry are among the most common entangling items from plastic debris. Since the ultimate focus of this study is testing the newly developed CF for entanglement, data on plastic leakage for the investigated item is collected and incorporated into the system.

3.1.1 Functional unit

The functional unit (FU) of the study was defined as "1 kg of landed cod caught with gillnet in Norway". The functional unit reflects the function of the plastic product, namely securing food for consumers by helping fishers catch their intended catch.

3.1.2 System boundary

This study is limited to cod caught with gillnets in Norway where processes occurring until the cod is landed are included. Commercial cod fisheries are occurring along the coast of Norway, however most of the catch is caught north of Stad (62 °N) and within the economic fishing zone of Norway (Johnsen, 2021). The geographic focus of this study is coastal fishing outside of Tromsø, a city in northern Norway which can be seen in Figure 5 under section 3.1.3. The study does not differentiate between the Northeast Arctic cod and the Atlantic cod, because the catch data gathered from the Directorate of Fisheries of Norway considers only cod.

Within the background processes, referring to the supporting activities further up in the value chain, gillnet production, fuel for the vessel, antifouling paint, boat paint, and marine lubricating oil are included (Figure 4). From investigating previous LCA studies on seafood, the choices of which processes to include was defined. The production of the gillnet was included in the system because the requirement of gillnets per FU was needed in order to quantify the leakage of gillnets to the ocean. The data requirements for the quantification was collected from an LCA study on seafood, whereas catch data was collected from the Norwegian Directorate of Fisheries

(Directorate of Fisheries, 2020a; Ziegler, 2002). Moreover, marine diesel consumption to fuel the vessel is shown to be a large contributor to overall environmental impacts in previous publications (Svanes et al., 2011; Winther et al., 2020; Ziegler, 2002). Because of this, production of fuel was included in the inventory and the data was collected from LCA studies from Norway. Additionally, processes linked to the maintenance of the vessel were accounted for as well. This includes antifouling paint, boat paint and marine lubricating oil. These processes have been included in previous studies and due to available data, these processes were accounted for. Also, these processes can, due to abrasion of for instance antifouling paint, leak to the ocean and impact marine animals through ingestion of microplastic. However, this impact pathway and loss of microplastic is not assessed in this study. Previous LCA studies on seafood products report that the production of the fishing vessel do not contribute as much as the fuel consumption to the overall impacts (Vázquez-Rowe et al., 2010; Ziegler, 2002), and due to lack of accurate data, the construction of the vessel and engine are excluded from this study.

The foreground is the direct processes related to the system. Here, fishing activity was included, whereas processes happening after the fish is caught were not accounted for. Regarding the outputs from the process “fishing activity”, direct emissions from fuel combustion and gillnets lost to the ocean are considered within the system boundary, whereas collected gillnets for waste handling, as well as retrieved gillnets from the ocean are outside the system boundary. The reason being that the overall focus of this study is to quantify the leakage and possible effects of plastic debris on marine species, where if lost, gillnets may continue to trap and entangle marine animals.

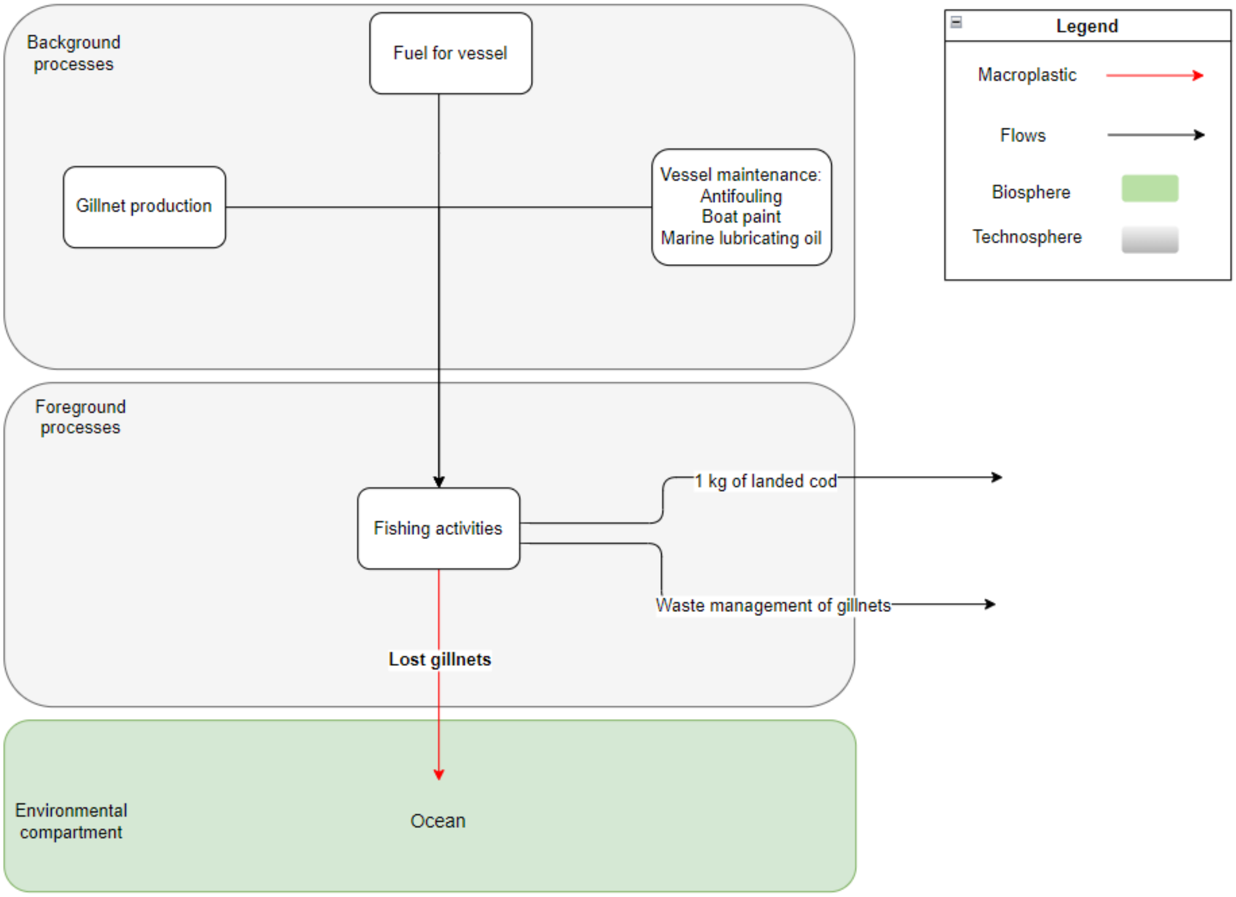

Figure 4 - System boundary of the investigated study. The black arrows represent exchanges within the technosphere, and the red arrow represents an exchange between the technosphere (fishing operation) and the biosphere (ocean). The grey colour refers to the foreground and background system, whereas the green colour is the biosphere with ocean as the environmental compartment.

3.1.3 Study area

For the determination of the location at which the loss of gillnet occurs in this study, hotspots for fishing activity in Norway were explored using an interactive map explorer provided by the Norwegian Directorate of Fisheries. Data was limited to fishing activity by gear (net) and coastal fishing spots for passive fishing gear, i.e., gillnets among others, along the coast. From this, a data point outside Tromsø was defined (see Figure 5).

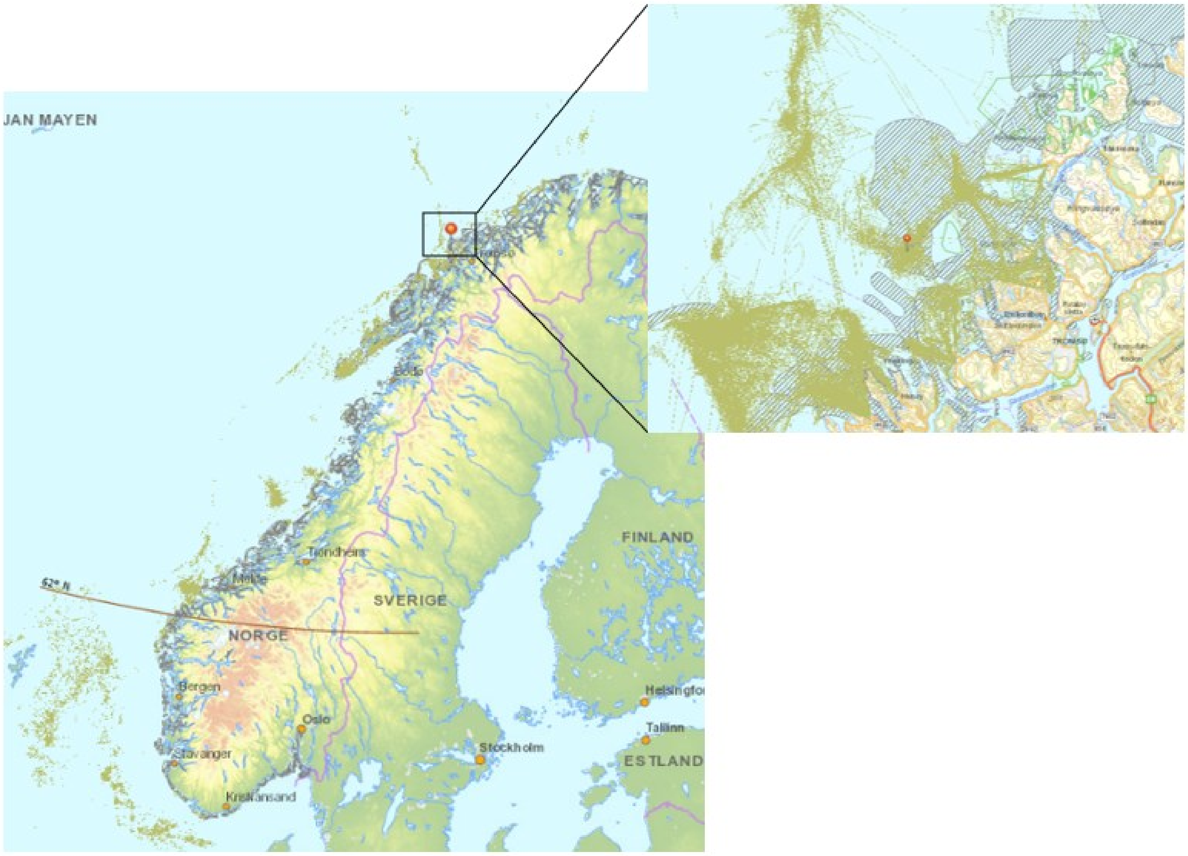

Figure 5 - Fishing activity hotspots along the coast in Norway. Green areas show hotspots of fishing activity with nets, and the grey areas show hotspots of fishing with passive gears, such as nets, in coastal areas. The red marker represents the location of gillnets lost to the ocean. Source: (Directorate of Fisheries, n.d.).

3.2 Assumptions and limitations

The main assumptions of the study are:

- Due to the focus of the study, processes occurring after the fish is caught, such as processing, packaging, transport to final consumer, and finally waste management of the packaging is not considered.
- The construction of the vessel and engine are excluded from the inventory because the production of these processes is shown to be less significant for the overall impacts (Vázquez-Rowe et al., 2010; Ziegler, 2002).
- The waste management of gillnets are not accounted for.
- Retrieved gillnets are not considered. The fishing gear can be retrieved after it is lost, however this flow is not accounted for in this study.

- It is assumed in this study that the loss of gillnets ends up in the ocean upon its initial release. Fishing gear may be redistributed to for instance beaches. However, this is not considered.
- Only cod caught by the Norwegian fishing fleet is investigated. International vessels and recreational vessels are outside the system boundary.
- Bycatch and loss of fish are not accounted for.
- The composition of lead in a gillnet is excluded in the study because the main entangling item is the net itself.
- Other plastic losses to the environment such as plastic pellets from production of plastic polymers, tire abrasion during transportation, and losses of microplastic due to abrasion of antifouling paint are excluded due to lack of sufficient data.

3.3 Life cycle inventory analysis

To collect relevant data for the inventory, a literature review was conducted. Specifically, the focus of the literature review was to collect data for plastic litter since these flows are not considered in existing LCI datasets. The data collection started with investigating loss rates i.e., how much of the fishing gear is lost during deployment, and the weight of a gillnet as well as the number of nets needed to meet the functional unit. Deshpande et al. (2020) determined the plastic flows from Norwegian fisheries using material flow analysis (MFA). For the determination of the final loss rate of gillnets lost in Norway, a value from Deshpande et al. (2020) was applied. Furthermore, the composition of materials in a gillnet, lifetime of a net as well as fuel use for a vessel fishing for cod in Norway were defined (Schau et al., 2009; Winther et al., 2020; Ziegler, 2002). Additionally, vessel maintenance requirements such as antifouling paint, boat paint, and marine lubricating oil were included (Svanes et al., 2011). Secondary data was obtained from the Ecoinvent 3.8 database (Wernet et al., 2016). Although recent data were preferable, the data gathered for the inventory in this thesis are from the years 2002 to 2020.

3.3.1 Gillnet production

Fishing gear is divided into active and passive, where active gear actively target the fish using trawl or seine, whereas passive gear such as gillnet, lines or pots are fixed where the fish seeks the gear (Deshpande et al., 2020). A gillnet is a net consisting of a line with floaters at the top of the net, and weights to stabilize the net at the bottom (Directorate of Fisheries, 2010; Hennøen, 2016). The properties of a gillnet, such as mesh size, length, and height, vary depending on the target catch. Gillnets used for targeting cod are usually called bottom-set gillnets or set gillnets which are fixed to the seabed by anchors and lead ropes. These nets are usually large-meshed and made of nylon (Hennøen, 2016). Other types of gillnets include driftnets and midwater gillnets. The average lifespan of a gillnet is between 1.5 and 2 years (Deshpande et al., 2020; Ziegler, 2002).

Ziegler (2002) estimated that a gillnet consists of a nylon net (6 kg), rope made of light density polyethylene (LDPE) (4 kg), and lead (8 kg). Including the lead, the weight of a gillnet is 18 kg. According to Deshpande et al. (2020) the material composition of a gillnet excluding the lead parts is 80% nylon net and 20% rope.

The estimations of the material composition by Ziegler (2002) are used in this study to calculate the amount of gillnet needed to fish 1 kg of cod (Table 1). As previously mentioned, the lead parts in a gillnet are excluded in this study. The lifetime of a gillnet was set based on Ziegler (2002), thus 1.5 years for the nylon net and 4.5 years for the rope. Standal et al. (2020) reported that vessels below 11 meters in length using gillnets as their main gear when fishing for cod, use between 80 and 100 gillnets per trip. An average of this was used in the study, giving 90 gillnets per fishing trip (Table 1).

Catch data for Norwegian fisheries was collected from the Norwegian Directorate of Fisheries. Based on statistics for the year 2020, data was retrieved for the mass of cod landed with conventional vessels below 11 meters as well as the number of vessels (Directorate of Fisheries, 2020a). For this study, the mass-based allocation method was applied and considered the most relevant approach because of the functional unit being landing of cod during fishing. The catch data report that from 1215 vessels, 82 070 ton of fish was landed north of 62°, whereof 40 621 ton was cod (Directorate of Fisheries, 2020a). Since about half of the catch caught was cod, it is assumed in this study that half of the vessels normally target demersal species such as cod. Owing to this, the amount of catch per vessel is then 66.7 ton of cod (Table 2).

Table 1 – Fishing gear data including material composition, weight, lifetime, and the number of gillnets per fishing trip.

Fishing gear data	**Value**	**Unit**	**Calculation**	**Reference**
Net (nylon)	6	kg		(Ziegler, 2002)
Rope (LDPE)	4	kg		(Ziegler, 2002)
Gillnet weight	10	kg		
Lifetime nylon net	1.5	years		(Ziegler, 2002)
Lifetime rope	4.5	Years		(Ziegler, 2002)
Gillnets per trip for vessels < 11m	90	Gillnets/trip		(Standal et al., 2020)
New nets every year	45	Nets/year	$\frac{90\ {gillnets}/{trip}}{2\ years}$	
New ropes every year	20	Ropes/year	$\frac{90\ {gillnets}/{trip}}{4.5\ years}$	

Table 2 - Catch data (2020) for landed cod in Norway north of 62°N. Source: (Directorate of Fisheries, 2020a).

Catch data	**Value**	**Unit**	**Calculation**
Cod landed in 2020 with conventional vessels <11m	40 492	ton	
Vessels <11m	1 215	Number of vessels	
Catch per vessel	66.7	ton	$\frac{40\ 492\ ton}{1\ 215/2\ vessels}$

Table 3 – Quantification of the requirement of gillnet per FU.

Gillnet requirement to meet the FU	**Value**	**Unit**	**Calculation**
Net (nylon)	5.4	g/kg	$\frac{45\ {nets}/{yr} * 6\ kg}{66\ 700\ kg} \times 1000$
Rope (LDPE)	1.2	g/kg	$\frac{20\ {nets}/{yr} * 4\ kg}{66\ 700\ kg} \times 1000$
Total	6.6	g/kg	$5.4\frac{\mathrm{g}}{\mathrm{kg}} + 1.2\frac{g}{kg}$

The requirement of 6.6 g gillnet/kg of landed cod (see Table 3) is consistent with values in other studies. Loubet et al. (2022) reported that sole caught with gillnets require 72.1 g gear/kg fish at the consumer stage and so at the fishery stage the requirement would be lower, and according to Kuczenski et al. (2022) the gear usage intensity is 14.7 kg*year gear/ton of catch for set gillnets.

3.3.2 Lost gillnets

There are spatial differences regarding loss rates for fishing gear. Loss rates from publications and reports were explored (see Table 4), primarily for Norway but a global estimate was considered for comparison. The most recent and relevant value from Deshpande et al. (2020) was applied in this study as an average of the given percentages, i.e., rate of loss is 1.5% for gillnets. It is important to note that the loss rates can vary depending on the location, and that the loss rate found in Deshpande et al. (2020) was for fishing activity between Bergen and Trondheim, i.e., mid and western Norway. However, the fishing spot focused on in this study was outside of Tromsø, which is further North (see Figure 5). The Plastic Leak Project (PLP) differentiates stages of plastic release to the ocean into initial and final release (Peano et al., 2020). Fishing gear will in most cases be lost to the ocean, which is the environmental compartment at the initial release. Furthermore, it can be redistributed, either by ocean currents to other geographical locations, or it may end up at beaches or shorelines, reaching its final release compartment (Peano et al., 2020). In this case, only the initial release compartment is considered, meaning that the study assume that the gillnets are lost to the ocean. Other types of plastic, such as plastic pellets from production processes can for instance leak into a river and then be transported to the ocean upon its final release.

Table 4 - Loss rates for gillnets for Norway and on a global scale.

Location	Loss rate	Type of gear	Comments	Reference
Norway	1% - 2%	Gillnets	Percentage annually	(Deshpande et al., 2020)
Norway	0.02%	Gillnets	Nets/boat/yr	(Macfadyen & Huntington, 2009)
Global	5.8%	Gillnets, entangling nets	Percentage annually	(Richardson et al., 2019)

The calculation of the flow "lost gillnets to the ocean" is based on the mass of gillnet deployed per kg of landed cod and the estimated loss rate, i.e., 6.6 g gillnet/kg landed cod and 1.5% loss rate gives 0.1g gear lost/kg cod:

$$6.6\ \frac{g}{kg} \times 1.5\ \% = 0.1\ \frac{g}{kg}$$

3.3.3. Fuel use

Fuel use during fishing operations is often a major contributor to emissions in fisheries. Fuel consumption varies greatly depending on fishing gear and vessel type (Suuronen et al., 2012; Winther et al., 2009). The commercial fishing fleet in Norway is divided into ocean fishing with vessels longer than 28 meters using trawl and purse seine as their main fishing gear, and the conventional fleet with vessels smaller than 28 meters in length and use conventional fishing gear such as gillnets and pots (Syversen et al., 2020; Winther et al., 2020). According to research passive fishing gears use less fuel per kg of landed catch than active fishing gears such as trawls (Suuronen et al., 2012). Active fishing gear usually require larger vessels with more powerful engines, consequently needing more fuel (Thompson, 2017). Gillnet fisheries usually operate with relatively small vessel with average lengths between 10 and 14 meters (Norwegian Seafood Council, n.d.; Thompson, 2017). Cod is mainly caught along the coast (Thompson, 2017), with vessels from 9 to 16 meters in length (Clegg & Williams, 2020). Therefore, this study considers the coastal fleet fishing with gillnet using vessels below 11 meters.

Estimates for fuel consumption have been made for different LCA studies on gillnet fisheries. A report from Sintef estimated fuel consumption based on vessel type and target species (Winther et al., 2020). They found that coastal conventional vessels use approximately 0.13 liter fuel per kg of liveweight fish, and in general vessels catching cod use 0.189 liter fuel per kg of liveweight fish (Winther et al., 2020). Other publications report of requirements of 0.19 kg fuel per kg of groundfish including cod caught with gillnet (Schau et al., 2009), and 0.34 liter fuel per kg of cod caught with gillnets (Ziegler, 2002).

The fuel consumption estimates obtained by Winther et al. (2020) (0.13 l fuel/kg fish), and Schau et al. (2009) (0.19 kg fuel/kg fish) are considered the most relevant for the purpose of this study because these studies are from Norway. The value of 0.13 l fuel/kg liveweight fish is converted to kg fuel/kg liveweight using a diesel density of 0.84 kg/l (Winther et al., 2020), providing a fuel consumption of 0.12 kg/kg fish. A fuel consumption value was estimated taking the average of the latter publications, resulting in a value of 0.15 kg fuel/kg landed cod.

The background processes are collected from the Ecoinvent 3.8 database, with the dataset "Diesel, low-sulphur (Europe without Switzerland) | market for | Cut-off,". The choice of this Ecoinvent dataset is based on a report on greenhouse gas emissions of Norwegian seafood products in 2017 (Winther et al., 2020). The combustion of fuel in the vessel is modelled with emission factors for marine diesel oil. This is explained in the next section, 3.3.4.

3.3.4 Direct emissions from fuel use during fishing operation

During fishing operation, direct emissions will occur due to fuel combustion. Emission factors for marine diesel oil were collected from Statistics Norway (Table 5) (Statistics Norway, 2017), where these factors are multiplied with the fuel consumption value of 0.15 kg fuel/kg cod. The emissions included are carbon dioxide (CO_2), sulphur oxide (SO_2), methane (CH_4), nitrogen oxide (NO_x), carbon monoxide (CO), and non-methane volatile organic compounds (NMVOC). Table 6 shows the direct emissions which are based on the emission factors in Table 5. The specific calculation of the direct emissions can be found in Appendix 4.

Table 5 - Emission factors for marine diesel oil. Source: (Statistics Norway, 2017).

Emissions	**Value**	**Unit**
CO_2	3,17	kg/kg fuel
SO_2	1,16	g/kg fuel
CH_4	0,23	kg/ton
NOx	43,76	kg/ton
CO	2,9	kg/ton
NMVOC	2,4	kg/ton

Table 6 - Direct emissions to the atmosphere from diesel combustion in the fishing vessel. The values are in unit per FU.

Emissions to atmosphere	**Value**	**Unit**
CO_2	475,50	g/kg
SO_2	0,17	g/kg
CH_4	0,03	g/kg
NOx	6,56	g/kg

CO	0,44	g/kg
NMVOC	0,36	g/kg

It is important to note that emissions from production processes in the background system, for example the production of fuel, antifouling paint, boat paint, and gillnet are accounted for, taken from the Ecoinvent 3.8 database (Wernet et al., 2016). The name of the datasets can be found in Appendix 1.

3.3.5 Vessel maintenance

Antifouling paint, boat paint, and marine lubricating oil were included in the inventory. Fishing vessels are usually coated with antifouling agents to prevent algae growth and attachment (Ellingsen & Aanondsen, 2006). During fishing activities, the fouling leaks to the ocean in the form of microplastic. Vázquez-Rowe et al. (2010) reported that antifouling and boat paint were important factors to include in the assessment of fishing operation because vessels go through maintenance once a year. A study by Svanes et al. (2011) report of values of 0.03 g antifouling paint per kg of caught fish and 0.12 liter boat paint per ton of caught fish mainly fishing for cod with longline in Norwegian waters. The estimations applied in this study is based on Svanes et al. (2011), due to the geographical location. The value for boat paint is converted from liter to kg using a density of 1.6 kg/L (Borum, n.d.), giving a value of 0.192 kg of paint per kg fish.

In Ecoinvent 3.8 there are several datasets for paint, however, no clear dataset for antifouling paint. Because of this, the dataset “market for antifouling paint emissions” was used. The dataset represents treatment of the emissions occurring from antifouling paint, where the values are negative. Therefore, when applying the value of 0.03 g/kg in this study it was set to be -0.03 g/kg, as done in other datasets in Ecoinvent 3.8, for example “hake, capture by long liner and landing whole, fresh”, where the input of antifouling paint emissions was set to be negative as well.

Values for marine lubricating oil was taken from the same study, with a requirement of 0.9 l/ton of cod (Svanes et al., 2011). This value was converted to kg using a density of 800 kg/m3, giving 0.72 g per kg of fish (Svanes et al., 2011). The calculation of the conversions of marine lubricating oil and boat paint can be found in Appendix 3.

3.4 Brightway software

Brightway version 2 (Brightway2) is the software used to calculate LCA results with Ecoinvent 3.8 as the database. Brightway2 is an open source platform for LCA studies and is based on the programming language Python (Steubing et al., 2020). The Activity Browser (AB) is a program based on the Brightway framework and works as a productivity tool for Brightway (Steubing et al., 2020). The user can import databases, for example versions of Ecoinvent, search for activities and by using a drag-and-drop approach, collect the relevant exchanges from the technosphere and biosphere. The AB also provides the user with a graphical setup of the system with different colour codes for the activities, called graph explorer. The graph explorer enables the user to explore the supply chain of an activity to get an understanding of the supporting processes. Regarding the colour codes used, black represent a producing activity, red is waste treatment, orange is market, and yellow is market group (Steubing et al., 2020).

In this study, the AB was used to set up the system, define exchanges from activities and visualize the system in graph explorer (Figure 6). The reason for using the AB for the setup of the system was for establishing the project and database to model the life cycle inventory more efficiently since the AB is more productive for these tasks (Steubing et al., 2020). The AB is more efficient for standardized tasks since the software is doing the programming, whereas in Brightway2 the programming needs to be performed by the user. Additionally, the AB was used for when obtaining results for process contributions. Moreover, for the exchange of lost gillnets between the fishing activity and the ocean and the implementation of the CF for entanglement provided to the author of this thesis, the work continued in Microsoft Excel, hereafter Excel, for the final LCA results.

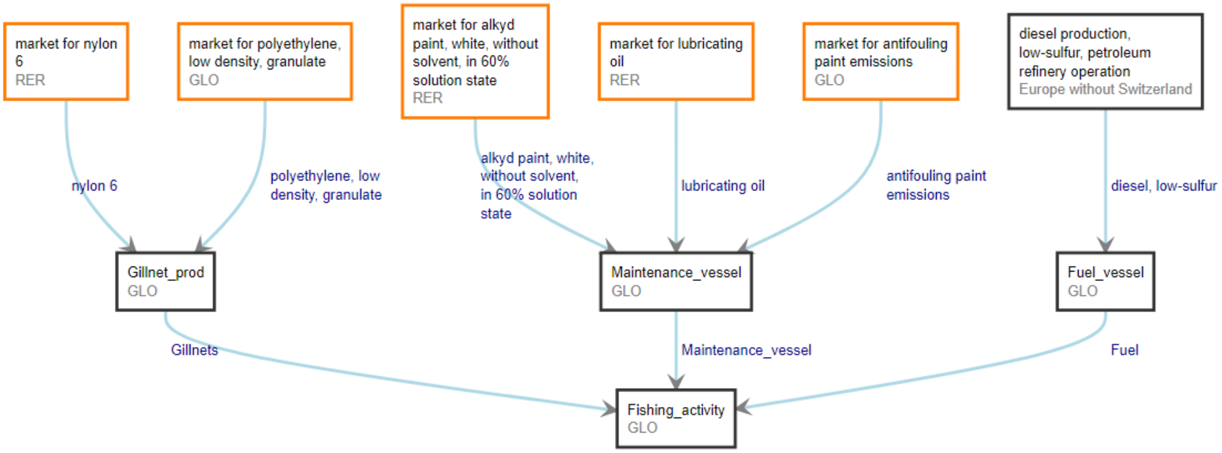

Figure 6 - Graphical view of the system.

3.5 Life cycle impact assessment

The impact methodology applied in an LCA study can affect the results to a large degree. The choice of method is therefore important. Brightway2 stores LCIA methods, provided by the Ecoinvent centre, which can be used for LCA calculations (Mutel, 2016). The LCIA methodology retained is the ReCiPe 2008 method, as this is the version of ReCiPe Ecoinvent version 3.8 is using (ecoinvent Association, 2021), which covers 18 midpoint categories allocated to three AoP (Huijbregts et al., 2017). An advantage of applying ReCiPe to this study is because the method is local, as well as present in Brightway2. This study focuses on ecosystem quality as the AoP with a hierarchist perspective. At the endpoint level, Ecoinvent 3.8 has normalised the values where the unit is given in "points". In order to be able to compare the impact categories at endpoint with the impact of entanglement from lost gillnets, the unit must be the same and in "species.year". Because of this, Excel was used for the final calculations of the results at an endpoint level in the unit species.year. To do this, results were obtained at a midpoint level using Brightway2. Further, these midpoint results were exported to Excel and by using conversion factors for midpoint to endpoint for ReCiPe 2008 provided by ReCiPe (The National Institute for Public Health and the Environment, 2017), results were calculated in species.year. The impact categories included at an endpoint level are shown in Table 7. The conversion factors and the results at midpoint and endpoint level can be found in Appendix 7.

Table 7 - Impact categories investigated at endpoint in species.year.

Investigated impact categories at endpoint	**Unit**
Global warming	Species.year
Marine ecotoxicity	Species.year
Freshwater ecotoxicity	Species.year
Freshwater eutrophication	Species.year
Terrestrial ecotoxicity	Species.year
Terrestrial acidification	Species.year
Entanglement	Species.year

Regarding the potential entanglement impacts generated by discarded or lost gillnets to the ocean, a preliminary impact category for entanglement was included. Here, a leakage rate was applied for the quantification of lost gillnets to the ocean. This impact category requires a characterization factor based on the fate and effect of the debris (Woods et al., 2019). The setup of the regionalized LCIA model and development of the CF was done by Marthe Alnes Høiberg. The CF for entanglement was estimated based on information and data from van Sebille et al. (2012) and Høiberg et al. (2022). Regarding the fate modelling, data was from van Sebille et al. (2012) and their corresponding “PlasticAdrift” model, reflecting the distribution of plastic debris in the ocean once discarded from certain locations. For the effect modelling, Høiberg et al. (2022) and the species sensitivity distribution (SSD)-based model for entanglement from plastic debris was the base for the modelling. An overview of the conversion steps from PAF/m2 to species.year/kg emitted plastic can be found in Appendix 6.

3.6 Sensitivity analysis

The parameter which may influence the results and considered relevant to test was the loss rate. This is because the loss rate differentiates in literature based on location as well as when the study was conducted. The sensitivity of this parameter was tested by both increasing the value to a global loss rate (5.8%) (Richardson et al., 2019) and decreasing the parameter to a lower loss rate for Norway (0.02%) (Macfadyen & Huntington, 2009).

4 Results

4.1 Inventory results

The results from the life cycle inventory given per FU are shown in Table 8. The inventory results showed that 6.6 g of gillnet is required to land 1 kg of cod at the fishing stage. Direct emissions arising from fuel combustion in the vessel during fishing operation are accounted for in Table 8 under outputs. These emissions, CO_2 in particular, constitute a large part of the emission inventory (Table 8). Figure 7 reflects the quantified system where the processes of antifouling paint, boat paint, and marine lubricating oil represents the vessel maintenance flow, i.e., 0.942 g. A detailed inventory of the system can be found in Appendix 2.

Table 8 – LCI for the present study on a gillnet fishery in Tromsø, Norway. FU is 1 kg of landed cod with gillnet in Norway.

Inputs from technosphere (every value is given per FU)	**Unit**	**Value (product)**	**Reference**
Fuel use (marine diesel oil)	kg	0.15	(Schau et al., 2009; Winther et al., 2020)
Gillnet	g	6.6	(Directorate of Fisheries, 2021, 2022; Ziegler, 2002)
Antifouling paint	g	0.03	(Svanes et al., 2011)
Boat paint	g	0.192	(Svanes et al., 2011)
Marine lubricating oil	g	0.72	(Svanes et al., 2011)
Output: product			
Landed cod	kg	1	
Outputs: direct emissions from fishing activity			
Lost gillnets	g	0.1	
CO_2	g	475.5	
SO_2	g	0.17	
CH_4	g	0.03	
NOx	g	6.56	
CO	g	0.44	
NMVOC	g	0.36	

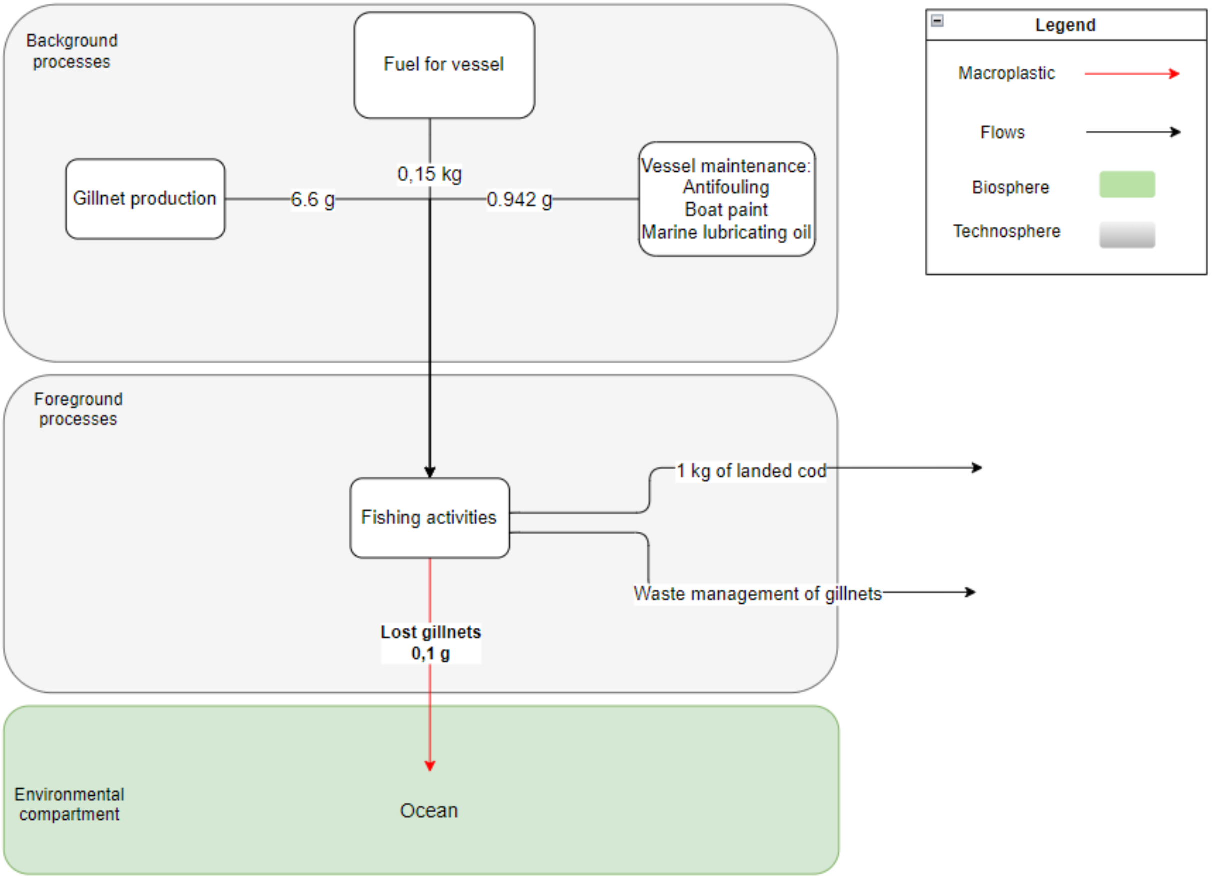

Figure 7 - Quantified system. The grey color represents the processes in the background and foreground. The green color refers to the ocean as an environmental compartment where lost gillnets enter.

4.2 Impact assessment results

4.2.1 Results at the midpoint level

The results in Figure 8 show the relative contribution of a process to the impact of each category obtained using the AB. The AB provide an overview of the process contributions for the investigated system, where a "rest" category refers to the cut-off level which in this case was set to be 6.3%, as this is the default cut-off level set by the AB. This means that processes which contributes with less than 6.3% to the specific impact category is within the "rest" category. As seen in Figure 8, the fishery phase dominates the global warming category, which is mainly due to the direct emissions that occur during combustion of fuel in the vessel. In addition, the production of nylon used in gillnet production contributes to global warming through emissions of greenhouse gases.

For marine ecotoxicity, the main contributors to the impacts are the treatment of antifouling paint emissions. Specifically, treatment of copper (Cu) and tin (Sn) as these are hazardous metals used in antifouling paint on vessels. These processes will have ecotoxic effects for the marine environment when they accumulate in the ocean.

The contributions to freshwater ecotoxicity are nylon production and different treatment processes of specifically water discharge from petroleum/natural gas extraction and sulfidic tailings. The latter refers to a waste material after ore processing. Emissions of different chemicals to freshwater will lead to toxicity.

Regarding the process contributions for freshwater eutrophication, the treatment of spoils from hard coal mining and lignite mining in landfills are resulting in impacts. These processes lead to freshwater eutrophication by emissions of phosphorous from processes such as diesel production, as well as nylon and polyethylene production for the gillnet.

Impacts related to terrestrial acidification arise from fishing activity, nylon production for the gillnet, diesel production, as well as treatment of waste from natural gas and transport of petroleum. Through accumulation of nutrients, for instance nitrogen and sulphur, in terrestrial ecosystems these processes contribute to impacts.

Regarding terrestrial ecotoxicity, diesel production, treatment of water discharge from petroleum/natural gas extraction, soybean production, and treatment of drilling waste during landfarming are the process contributions. Soybean production comes from production of boat paint, where the process for alkyd paint in Ecoinvent 3.8 requires soybean oil. In the same way as for freshwater ecotoxicity, it is the emissions of chemicals which will lead to ecotoxic effects.

An attempt at including the leakage of gillnets is shown in Figure 8. Since the leakage occurs at the fishery phase, the process of fishing activity is assumed to be the main contributor. Further, the leakage of gillnets at a midpoint level can lead to entanglement impacts at an endpoint level as the results in the next section will show. The "rest" category is not considered for gillnet leakage, and so the result should be cautiously interpreted. Overall, processes related to the production and use of diesel to fuel the vessel are the main contributors to the impacts.

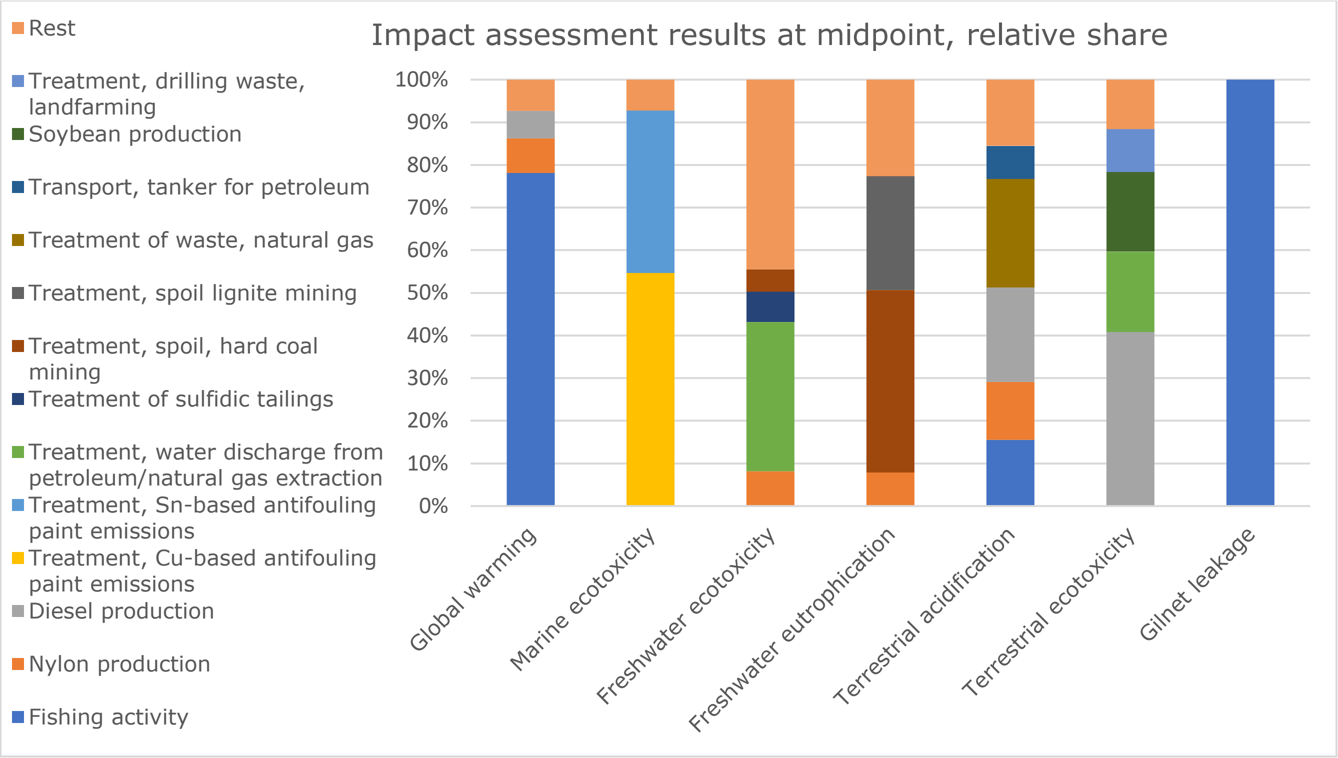

Figure 8 - Impact assessment results for the impact categories included. These results are at the midpoint level and provide an overview of the process contributions to the different impact categories. Cur-off level is at 6.3%, meaning processes contributing to less than the cut-off level is within the rest category.

4.2.2 Results at the endpoint level

The main LCA results are summarized in Figure 9. The LCA results have been obtained using Brightway2 calculating the results at a midpoint level, using the ReCiPe 2008 hierarchist method. Furthermore, using conversion factors provided by ReCiPe 2008 (The National Institute for Public Health and the Environment, 2017), results at an endpoint level were calculated. At that stage, the impact category of entanglement was implemented obtaining results in species.year, referring to the fraction of potentially lost species per year.

According to the results shown in Figure 9, global warming is responsible for most of the environmental impact resulting in species loss per year, i.e., 4.8E-09 species lost. Moreover, the results show that the value for entanglement is significantly lower than the other impact categories, specifically 1.0E-27 species lost per year. Terrestrial acidification, terrestrial ecotoxicity, freshwater eutrophication, freshwater ecotoxicity, and marine ecotoxicity show results ranging from 3.2E-13 to 2.9E-12 species lost. Of these categories, terrestrial ecotoxicity is contributing the most, followed by terrestrial acidification, marine ecotoxicity, freshwater ecotoxicity, and freshwater eutrophication.

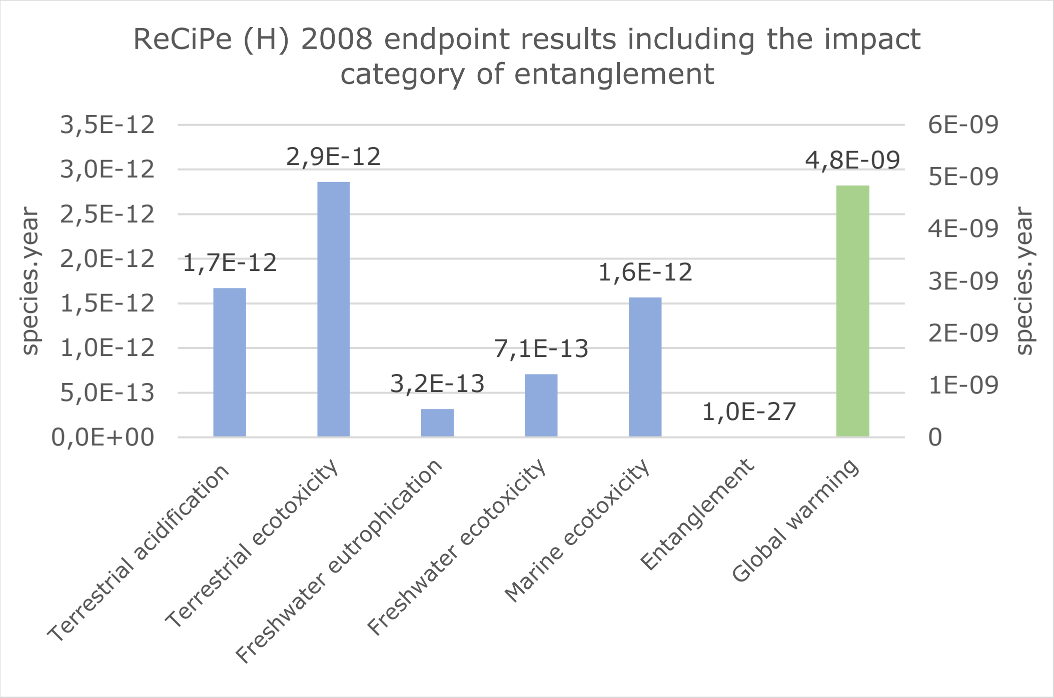

Figure 9 - LCA results using ReCiPe (H) 2008 at an endpoint level including the impact category of entanglement. The values on the right hand side are specifically for global warming as this result is higher than the other categories.

4.2.3 Results from sensitivity analysis

A sensitivity analysis was conducted by testing how the results would change by adjusting the loss rate of gillnets to an increased global value (5.8%) (Richardson et al., 2019), and an additional estimate for Norway (0.02%) (Macfadyen & Huntington, 2009). It is important to note that the parameters for the other impact categories were not altered and kept the same. First, the results for the global value indicate a higher fraction of lost species per year from entanglement when increasing the loss rate to 5.8% (Figure 10). The value is four times higher than the initial approximation, specifically 4.0E-27 species lost per year.

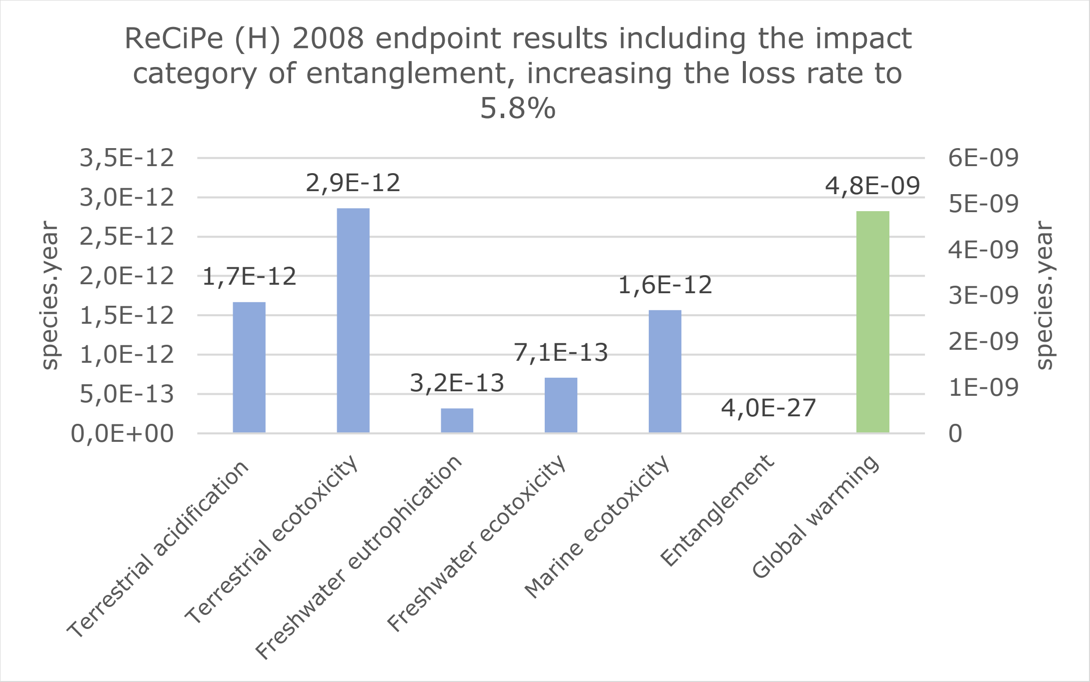

Figure 10 - LCA results at endpoint using ReCiPe 2008 in species.year. The loss rate is increased to a global average for gillnets, 5.8%. The values on the right hand side are specifically for global warming.

For the second analysis, the loss rate was decreased to 0.02%, a value based on a report on the magnitude, impact, and loss of ALDFG (Macfadyen & Huntington, 2009). The results, in Figure 11, showed a lower value of lost species due to entanglement. With a loss rate of 0.02% the fraction of lost species would be 1.4E-29 due to lost gillnets.

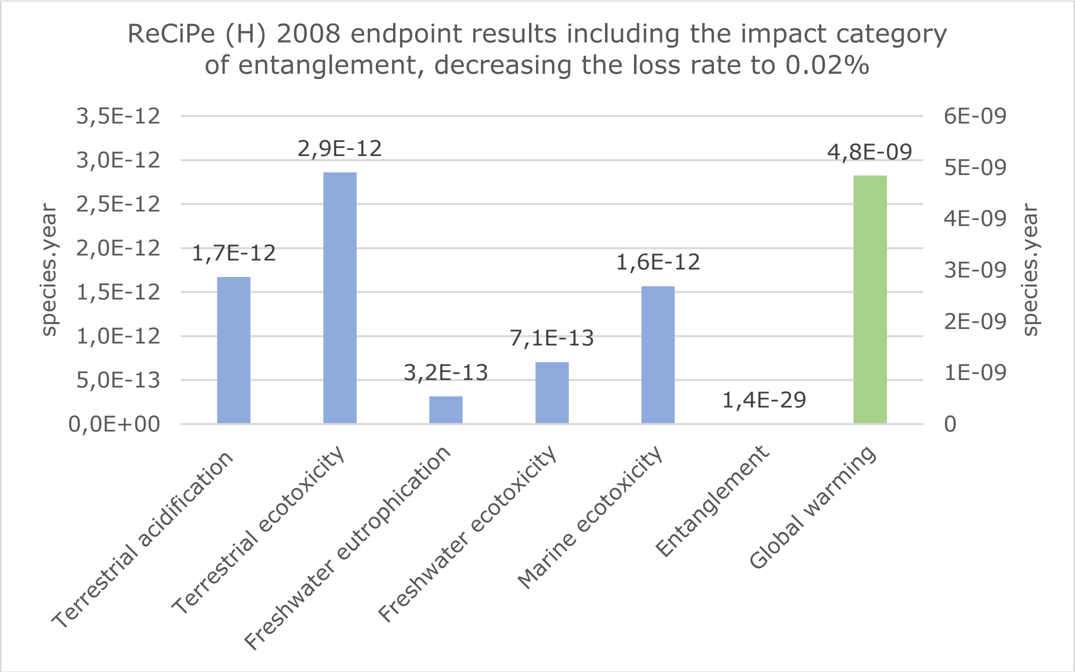

Figure 11 – LCA results at endpoint using ReCiPe 2008 in species.year. The loss rate is reduced to 0.02%. The values on the right hand side are specifically for global warming.

5 Discussion

5.1 Applied software and methodology choices

To date, no existing LCA studies have included emission flows of plastic at the impact assessment stage including entanglement as an impact category. Together with other unquantified impacts of mismanaged plastic, this represents a large knowledge gap within the LCA framework. Since marine plastic is not evenly spread out and ocean currents and winds influence the distribution, there is a need for regionalized assessments. During the last years, regionalized LCIA methods have been developed, namely ReCiPe 2016 (Huijbregts et al., 2017), LC-IMPACT (Verones et al., 2020), and IMPACTWorld+ (Bulle et al., 2019). Regionalized LCIA methods can contribute to enhance the accuracy of LCA studies and provide reliable results due to more accurate locations for policy makers to use (Frischknecht et al., 2019). Spatially explicit impact categories can be implemented to tackle the methodological gap and improve existing LCIA methods by expanding the number of impact pathways. For this particular study, this is attempted by testing the newly developed CF for entanglement as a potential impact pathway to biodiversity loss. The testing of the CF was done by altering the loss rate of gillnets.

Some LCA software, for instance SimaPro, do not allow for modifications of the system requirements and are fixed to the inventory of the database and existing LCIA methods. To be able to account for impacts occurring from plastic debris, a software where there are possibilities of adding methods and processes reflecting the user's requirements is needed. Brightway2 allow for modifications through being compatible with Python so that the user can for instance import LCIA methods and impact categories of choice and add or delete activities and exchanges. Additionally, the software is easy to use where the developers provide open access code examples. Moreover, the AB is a good productivity tool for Brightway2 which is easy to understand and use. For this study, the use of the AB sped up the process of defining the system with activities and exchanges, to be further used in Brightway2 and Jupyter notebooks. Brightway2 does, however, require knowledge of Python, in addition to Brightway2 being a relatively new and unexplored software for LCA calculations which is not applied in many existing LCA studies.

Regarding the process contributions, a cut-off level of 6.3% was used referring to the level at which processes contributing less than the cut-off level is categorized within a “rest” category, as shown in Figure 8 under section 4.2.1. The cut-off level used in this case was the default level used by the AB. There can be multiple processes within the rest category, however, they are less significant compared to the other processes. Lowering the cut-off level can provide more detailed information about all the processes contributing to the specific impact categories. The intention here was to show the top contributing processes for each investigated impact category.

5.1.1 Limitations

There are uncertainties related to the choice of processes in the background system because these processes have been collected from the Ecoinvent 3.8 database, representing a lack of accuracy in the data collection phase. For example, the requirement of boat paint to maintain the hull of the vessel has been collected from literature, however, information regarding which dataset to choose in Ecoinvent was not described in said literature. Therefore, the choice made of which Ecoinvent dataset to represent boat paint could be partial. Moreover, the decision of which processes to include within the system boundary and which to exclude was based on data availability in existing literature. The quantity and requirements of the different flows and processes included differs in literature due to different catch data for that specific fishery. Therefore, the choices made regarding the processes and the associated quantities included in this study represents inaccuracies.

Regarding the entanglement category, the associated CF can likely be considered a conservative estimate. Firstly, it considers entanglement in macroplastic in general, meaning the CF does not currently differentiate between whether the plastic item is a gillnet or for instance a packaging band, both items known for causing entanglement impacts. If it related specifically to the concentration of lost fishing gear instead of all macroplastic, the effect factor (EF) value would likely be much larger. Secondly, an explicit exposure factor, i.e., the potential exposure to sensitive species in a specific natural environment (Hauschild & Huijbregts, 2015), is not included as a separate factor in the CF, which currently consists of an effect factor (EF) and a preliminary fate factor (FF).

There were limitations regarding the choice of LCIA method when conducting the LCA. Firstly, the ReCiPe 2008 version is used by Ecoinvent 3.8 instead of the newer version of ReCiPe 2016. Because of this, fewer impact categories at endpoint have been considered since there are conversion factors for only a selection of impact categories for the 2008 version of ReCiPe, namely global warming, freshwater ecotoxicity, freshwater eutrophication, terrestrial acidification, terrestrial ecotoxicity, and marine ecotoxicity. Categories available for the 2016 version of ReCiPe is in addition to the abovementioned: photochemical ozone formation, water consumption for terrestrial and aquatic ecosystems, land use occupation, land use transformation, and marine eutrophication. These impact categories are important to account for as well. The outcome of this is less representation of impact categories at an endpoint level where the results do not cover as many categories as preferred. It is also important to note that some of the categories at midpoint are only relevant to the AoP of human health and resource depletion, including ionizing radiation, particulate matter formation, and metal depletion.

Secondly, for the ReCiPe 2008 method at endpoint level, Ecoinvent 3.8 has normalized the values where the unit is given in “points”. Normally, it would be expected that the unit is species.year, referring to the loss of species per year, for this LCIA method. Uncertainty regarding interpretation of the results can arise when the unit is weighted and normalized to a single score. LC-IMPACT is another LCIA method at endpoint where the values are in PDF (potentially disappeared fraction of species). However, this LCIA method is not present in Brightway, and need to be imported by the user.

In this study only fishing gear, and specifically gillnets were explored. Other plastic debris, namely packaging items such as bands, straps and six-pack rings affect marine life through entanglement. Additionally, other types of fishing gear generate entanglement impacts as well. These aspects should be further investigated by future research.

5.2 Interpretation of the inventory results

5.2.1 Comparing gear usage intensities and loss rates with similar studies

The requirement of 6.6 g of gillnet to catch 1 kg of cod show similar results as other studies. Other publications report of 14.7 kg*year/ton of fish as the gear usage intensity for set gillnets

(Kuczenski et al., 2022), whereas Loubet et al. (2022) report of a requirement of 72.1 g gear/ kg of fish for trammel nets which are similar to gillnets. The value estimated in the latter study is at the consumer stage meaning the requirement would be lower at the fishery stage because less gear is required to land 1 kg of fish than only parts of the fish. As Loubet et al. (2022) emphasized, fishing gear, such as gillnets and longlines, require a considerably higher amount of gear per kg of fish landed compared to other gears, consequently contributing to higher plastic losses.

Gillnets have a lower loss rate compared to other fishing gears, for example longlines and trawl nets. On a global scale gillnets have a loss rate of 5.8%, longlines have 20%, and trawls have 12% (Richardson et al., 2019). However, the losses of trawls arise from net fragments and do not constitute losses of whole nets. Contrary to passive gears, it is more common to loose fragments rather than the whole net for active gear such as trawls, mainly due to the gear becoming ensnared when in contact with the seabed (Richardson et al., 2019). Deshpande et al. (2020) conducted a material flow analysis (MFA) of plastic flows from the fishing industry in Norway and show comparable results in terms of the difference in loss rates between the gears. Regarding deployment losses, longlines, pots, and traps have the highest rates of losses, ranging from 4% to 7%, trawls have 3%, purse seine nets have below 1%, Danish seine nets have between 1% and 2%, and gillnets have, as applied in this study, 1% to 2% (Deshpande et al., 2020). These loss rates indicate that gillnets are among the gear with the lowest rates of loss both on a global scale and for Norway. Nevertheless, according to Deshpande et al. (2020) gillnets are the gear most commonly lost or abandoned in Norway. The reason for this is that gillnets are cheap to buy and more commonly used by the commercial fishing industry than other gears, thus the extent of gillnets in the ocean goes beyond other gears.

Trawlers are documented to have a low gear usage intensity, specifically ranging from 0.451 to 5.55 kg*year gear/ton catch, whereas gillnets have a gear usage intensity of 14.7 kg*year gear/ton catch according to Kuczenski et al. (2022). Trawl nets do, however, entail a higher loss rate, i.e., 3% for Norway (Deshpande et al., 2020). Considering the loss rate applied in this study for gillnets (1.5%) and the estimation of lost trawls in Norway (3%), the loss of trawl nets as opposed to gillnets would be lower if the gear usage intensities mentioned above were applied. Given that potentially larger losses come from the deployment of gillnets due to the high requirements of gear per kg of catch, the risk of entanglement are significantly higher for gillnets compared to trawl nets. This conclusion is supported by studies reporting on considerable risk of ghost fishing by lost fishing gear where gillnets pose the largest risk (Gilman et al., 2021a; The Nordic Council of Ministers, 2020). Nevertheless, as previously mentioned trawls often lose fragments of nets which can impact the marine animals through ingestion.

5.2.2 Comparing different fishing gears and its potential for loss

A report on macroplastic losses from the fishing and aquaculture industry in Norway point out that passive gear, such as nets and longlines, are more susceptible to being lost compared to active gears, for instance trawls (Höjman et al., 2022). This is because passive gears are left in the ocean during operation and are vulnerable to weather and ocean currents. The gear can get attached to the seabed, for example to rocks, collide with other gear, or drift with ocean currents. Active gears, for example trawl nets and purse and Danish seine nets, are attached to the boat during fishing and may be lost due to a rocky seabed or undergo wear and tear (Höjman et al., 2022). Furthermore, the ability to catch fish after the gear is lost is maintained by gillnets, whereas trawls, Danish and purse seine nets, hook and line are less prone to ghost fishing after loss since the net consist of metal parts which makes them challenging to retrieve because they will sink (Deshpande et al., 2020; The Nordic Council of Ministers, 2020). Even though literature indicates that trawls and other active gear are less prone to being lost, further studies should review a full comparison of the potential for species loss due to entanglement for all fishing gears to enable reduction targets.

5.2.3 Plastic losses from other sources within this study

The loss of gillnets to the ocean occurs during fishing activity, i.e., in the foreground system. There are losses of plastics throughout the life cycle of the investigated fishery, for example plastic pellets from production of nylon in the background processes, microplastic losses from antifouling paint, fishing gear losses, emissions of microplastic from tire abrasion in transportation processes in the foreground system, as well as in the end-of-life phase where plastic losses of packaging items for storing the fish products can occur. Antifouling paint is recognized as a source of microplastic debris in the ocean originating from vessels. In Norway, the Norwegian Environment Agency has estimated that each commercial fishing vessel emits 300 tons of antifouling paint every year in the form of microplastic (Lusher & Pettersen, 2021). Emissions of microplastic in the form of antifouling paint can impact marine species through ingestion. Ingestion is not a part of this study, and therefore this study does not give a holistic view of the effect of marine plastic. This study only accounted for losses from fishing gear potentially leading to entanglement, however, the abovementioned losses are important to consider in terms of effects on marine life as well as the load of plastic debris in the ocean.

5.3 Interpretation of the impact assessment results

5.3.1 Identification of hotspots

Global warming was in this study the largest contributor to potentially lost species, with a value of 4.8E-09 species.year. This can be explained by the high requirement of diesel to fuel the vessel, resulting in high emissions of CO_2 amongst other gases. In addition, for freshwater ecotoxicity, freshwater eutrophication, terrestrial acidification and terrestrial ecotoxicity there were diesel related processes who accounted for the majority of impacts.

The availability of information on fuel consumption is high in fishery LCA studies where previous publications have reported that fuel consumption often is the main contributor to environmental impacts through high emissions of CO_2. Moreover, the requirement of fuel per kg of fish varies in literature. In Norway, studies report of fuel consumptions of 0.34 l/kg cod landed (Ziegler, 2002), 0.19 kg/kg fish landed (Schau et al., 2009), and 0.13 l/kg fish for coastal vessels (Winther et al., 2020). A study from Denmark documented that gillnet fisheries require 0.21 kg fuel/kg cod (Thrane, 2004). The abovementioned fuel consumptions are limited to gillnet fisheries and reflects similar requirements. Differences in fuel consumption depends on the type of gear used which again determines the size of the vessel. Additionally, the target catch influence the fishing gear requirements. For instance, a trawl can yield consumption of 0.28 kg fuel/kg fish (Schau et al., 2009) or 0.36 l fuel/kg liveweight catch (Winther et al., 2020). Trawl nets are used on large fishing vessels, often above 28 meters in length, consequently requiring larger engines generating high requirements of fuel (Thompson, 2017).

5.3.2 The relevance of including entanglement as an impact category and the effects of testing the CF for entanglement

The environmental assessment of a gillnet fishery in northern Norway, off the coast of Tromsø led to the finding that entanglement affect a low fraction of species compared to the other impact categories investigated in this study. The results showed that 1.0E-27 species per year can be lost due entanglement in lost gillnets. The result is based on the CF where the fate and effect of a macroplastic debris at a specific location have been considered. This means that the species in the areas where the gillnets have been lost and redistributed to, are at risk of becoming entangled, i.e., northern Norway and areas close to the Arctic. Since entanglement effects occur at an individual level, the events are not necessarily linked to entire species populations becoming affected. According to a study on entanglement of cape fur seals (*Arctocephalus pusillus pusillus*) in Namibia the rate of entanglement is shown to not impact the global population of cape fur seals (Curtis et al., 2021). However, a global review on entanglement of pinnipeds emphasizes that seven pinniped species have been shown to decrease, where six of these species have been documented with entanglements (Jepsen & de Bruyn, 2019). Four of these are reported endangered (*Neomonachus schauinslandi, Neophoca cinerea, Phocarctos hookeri, and Zalophus wollebaeki*), one is vulnerable (*Callorhinus ursinus*), and one is listed as least concern on the IUCN red list (*Arctocephalus gazella*) (Jepsen & de Bruyn, 2019). Because of this, it is important to acknowledge the potential of entanglement events impacting local, but potentially also global species populations adversely.

Ecosystems affected through global warming is happening on a global scale and is due to emissions of greenhouse gases that give rise to the earth's temperature, leading to damage on ecosystems and human health. On the contrary, entanglement is a regionalized impact pathway, meaning it happens at a specific location where it impacts the ecosystem in a specific area. In this study the plastic leakage was limited to one location and data point. As only one location was considered, the results need to be viewed with caution. First, the location of where the lost or discarded plastic item occur is a key factor for the potential impacts on marine species through entanglement. Areas with higher densities of species could experience higher fractions of species lost. Moreover, the density of plastic can be linked to extreme entanglement events in areas with high densities of plastic, such as areas around the garbage patches (Høiberg et al., 2022; Woods et al., 2019). Second, the specific loss rate related to the plastic item depends on the location of leakage. The results showed that the impact of entanglement in terms of species lost per year was minor compared to for instance global warming. However, this does not necessarily mean that leakage of gillnets in northern Norway is unlikely to lead to entanglement. In fact, Norway's marine biodiversity is proven to be abundant (Secretariat of the Convention on Biological Diversity, n.d.). The loss rate applied in this study was limited to Norway because of the gillnet leakage location. Areas with higher rates of lost gillnets and other plastic could potentially generate increased number of lost species due to entanglement. This was tested by altering the loss rate of gillnets leaking to the ocean. Changing the loss rate to a global value gave results four times higher than the initial fraction of lost species but the fate and effect was still limited to Norway, giving a fraction of 4.0E-27 lost species per year. Adjusting the loss rate to a lower value led to a fraction of 1.4E-29 lost species. The lower loss rate, however, was estimated in 2009 whereas the one applied in this study was taken from a publication from 2020. Fishing activities have, during the last years, increased and so the potential losses of gear have most likely increased as well. Therefore, adjusting the location to an area of high species sensitivity to entanglement as well as high densities of plastic debris could result in a significantly higher value of species lost due to entanglement in lost gillnets. This scenario was not considered in this particular study mainly because of the availability of catch data in Norway provided by the Norwegian Directorate of Fisheries, however, this should be considered in future studies.

It is important to keep in mind that the CF quantifies the potential loss of species due to 0.1 g of lost gillnet from one fishing vessel, which explains why this value must be low. Thus, the potential of 1.0E-27 species becoming lost due to entanglement is not for a whole net but only for a small part of it. Accordingly, the loss of a whole gillnet which adds up to approximately 10 kg excluding metal parts, could lead a higher fraction of lost species due to entanglement. It is also worth mentioning that the resulting number of impacted species from this study are from one vessel below 11 meters in length, fishing for cod off the coast of Tromsø in northern Norway. Hence, there are several assumptions and limitations regarding the gillnet fishery investigated in this study. In 2021 there were 5 633 commercial fishing vessels in Norway where most of them were located in Troms, Finnmark, and Nordland, i.e., the northern most counties in Norway (Directorate of Fisheries, 2022). In addition, of these fishing vessels, 4 503 are below 11 meters in length. However, not all these vessels are limited to catching cod, but a considerable number are. Just looking at Norway, the potential of entanglements in fishing gear is significant.

Additionally, international and recreational fishing vessels contribute to ALDFG as well, representing a major concern for the load of ALDFG in the ocean. Considering the total amount of lost gillnets as well as the amount of cod gillnet fisheries land in a year, combined with the fact that gillnets do not easily break down and can thereby continue to harm marine animals, the inclusion and relevance of plastic leakage and entanglement in LCA studies are significant.

Moreover, impacts of entanglement can also occur while the gillnet is active, meaning during fishing operation. In that case unintended catch, for instance a seal or a whale, may become entangled in the net by either swimming into the gillnet since the net is invisible to marine species (Deshpande et al., 2020), or attempt to catch already entangled fish. Several types of species have been reported as bycatch in gillnets, that is pinnipeds, sea turtles, waterbirds, cetaceans, and blue water fish (Žydelis et al., 2009). Furthermore, fishers are shown to have concerns about the potential of marine life becoming entangled while the gear is active (Richardson et al., 2021). Measures that could prevent and avoid entanglements in active gear includes reduced soak time for the gear, meaning how long the gear is deployed at sea, restrictions on fishing activities in specific areas, and actions to release entangled animals (Richardson et al., 2021). Additionally, in Norway sound transmitters are used to avoid bycatch of especially harbor porpoise (*Phocoena phocoena*) as these are commonly reported as bycatch as well as other marine mammals (Ministry of Trade Industry and Fisheries in Norway, 2021).

5.4 Implications and further research

There are to date limited information about the amount of plastic waste lost to the natural environment (Höjman et al., 2022). On the contrary, data on clean-ups and beach litter is usually more abundant (Höjman et al., 2022), provided by initiatives such as Fishing for Litter where fishing vessels retrieve lost or discarded fishing gear during operation (KIMO, n.d.), and Keep Norway Beautiful who focuses on clean-ups (Nordic Co-operation, n.d.). Marine debris collected from clean-up initiatives contribute to data collection on types of debris and in some cases also origin of the debris. In fact, litter found in northern Norway and around Svalbard, an island north of Norway, indicate that the majority originates from Norwegian and Russian fishing vessels operating in those areas (Höjman et al., 2022). The Nordic Council of Ministers (2020) note that it is difficult to estimate the amount of ALDFG in the ocean due to human factors such as tourism as well as ocean currents influencing the amount and distribution of macroplastic debris. Additionally, the plastic item's properties, for instance weight and size, determine the distribution of the debris (MacLeod et al., 2021). In that way, much of the plastics which are heavy will sink. It is widely cited that a large amount of the plastic debris in the ocean is on the seabed (The Nordic Council of Ministers, 2020). Therefore, it is important to focus on preventative measures such as reporting of gear deployments as well as clean-ups to recover lost debris. Nevertheless, Deshpande et al. (2020) highlight that retrieving derelict fishing gear on the seabed is avoided because it can potentially cause greater damage, for example damaging coral reefs.

In this study, only unintentional loss of gear is considered, however, deliberately abandoned fishing gear is also a cause for concern regarding the amount of ALDFG in the ocean (Deshpande et al., 2020). Deshpande et al. (2020) estimated that 380 tons of plastic leaks to the ocean from the commercial fishing industry in Norway every year. Additionally, international fishing vessels and leisure vessels are also contributing to ALDFG. Although commercial fishers are required to report on lost fishing gear, recreational fishers are not (The Nordic Council of Ministers, 2020). Fishing gear losses from recreational fishing vessels constitute a major source of ALDFG, where the fishing authorities have limited control. Thus, the results in this study might give an underestimation of the actual effect of lost gear.

There are several reasons why plastic originating from the fishing industry is leaking to the ocean in Norway, two of them being inadequate routines regarding waste onboard and that the handling of waste is a time-consuming process (Höjman et al., 2022). Additionally, fishers report of insufficient waste management solutions onboard the vessel and in the harbors. A report from Clean Nordic Oceans describes six areas which requires increased focus in order to reduce littering from the commercial fishing industry (The Nordic Council of Ministers, 2020). These include lack of reporting regarding the amount of and location of lost fishing gear, little effort to remove lost fishing gear, more focus on preventing loss of passive fishing gear since these are more susceptible loss, lack of incentives to inform fishers, lack of waste management systems for outdated or retrieved fishing gear, and no recycling of used or retrieved fishing gear. Based on this the Norwegian Directorate of Fisheries want to develop preventative measures such as providing insights for the consequences of littering, well-functioning waste management systems, annual clean-ups of lost fishing gear, developing biodegradable materials and research on the environmental impacts of fishing gears (Höjman et al., 2022).

Economic value play an important role in whether fishers actively prevent loss and maintain their gear (Höjman et al., 2022). Compared to gillnets, which are a passive and cheap fishing gear, trawl nets are expensive. As a result, the economic perspective represents an important incentive for fishers to retrieve and repair the gear if lost (Höjman et al., 2022). Since gillnets to some degree lack this economic incentive, they have a higher risk of being left in the ocean if it gets lost.

Gillnets remaining in the ocean can contribute to the depletion of fish stocks as well as entangle marine species. In literature there are suggestions of switching to biodegradable gillnets as opposed to the conventional nylon gillnet. A study concluded that biodegradable gillnets could lessen the potential of ghost fishing by degradation where microorganisms, namely bacteria, fungi and algae, in the marine environment contribute (Standal et al., 2020). These biodegradable gillnets are, however, more expensive than nylon gillnets, will catch less fish, and require more fuel per kg of landed fish. Since the choice of using biodegradable gillnets is optional in Norway, a fisher will make a rational choice of choosing the type of gillnet which is more efficient to use and less expensive. Hence, there is no economic incentive for gillnet fisheries to choose the biodegradable gillnet for the reason of reducing ghost fishing (Standal et al., 2020). In many LCA studies on seafood, including this study, fuel consumption is the main hotspot for environmental impacts (Laso et al., 2018; Svanes et al., 2011; Winther et al., 2020; Ziegler et al., 2003). It is therefore questionable in terms of emissions to implement the use of biodegradable gillnets if it generates increased fuel consumption per kg of landed fish. The suggestion of replacing nylon gillnets with biodegradable gillnets can be beneficial for sustainable gillnet fisheries to some degree and on long term, however, there are uncertainties regarding the degradation time of the net. Kim et al. (2016) estimated that the biodegradable gillnet would degrade after two years of being left in the ocean, where Grimaldo et al. (2019) questioned this conclusion as the use and wear of the gear was not accounted for. Nevertheless, there are possibilities of ghost fishing while the net is still whole. As such, it is important that the biodegradable net degrade entirely, otherwise it will decompose into smaller fragments (i.e., microplastic) and could potentially generate biodiversity losses through marine species ingesting these fragments. There can be beneficial outcomes of using both the nylon and biodegradable gillnet, although, focusing on preventative measures could be equally as important.

5.5 Data uncertainty

There are large uncertainties related to the data used for inventory in this simplified LCA study. The data for fuel use, gillnets, marine lubricating oil, antifouling and boat paint is based on literature attempting to extend the data inventory. The author acknowledges that these flows are very uncertain, and the results may be different if more accurate data was used, for instance by communicating with stakeholders and commercial fishers. It is important to note that this thesis is meant as a test of the characterization factor for entanglement, where the inventory was expanded to enable comparisons between the impact categories.

Catch data was simplified, where bycatch and other catch that fishers may have caught were excluded from the study, which to some extent provide uncertainties. Moreover, future studies should attempt at having a further detailed inventory to catch all relevant flows. For example, the production of the vessel was excluded mainly due to lack of accurate data as well as previous studies stating that this process is not as important as other processes in the overall impacts (Vázquez-Rowe et al., 2010; Ziegler, 2002). In addition, regarding the loss rate applied, fishing gear deliberately abandoned are not considered, only gear accidentally lost reflects the loss rate, representing uncertainties within the results as well.

6 Conclusions and further outlook

A simplified LCA of a gillnet fishery outside Tromsø in Norway has been conducted in this study. The environmental impacts associated with landing 1 kg of cod with gillnets have been compared with the newly developed CF for the impact pathway of entanglement. The knowledge gap of considering plastic losses as emission flows in LCA databases and LCIA methods has been explored, where several publications emphasize the need to develop the LCA framework as plastic leaking to the ocean is a major concern in terms of potential impact pathways, such as entanglement.

Revisiting the study's aim of accounting for the potential impacts of lost gillnets and testing the newly developed CF of entanglement, the results showed that 1.0E-27 species per year are at risk of becoming lost. Compared to the other investigated impact categories, the result for entanglement was significantly lower. The alteration of the loss rate to test the CF led to results of 4.0E-27 species lost per year with a higher loss rate, and 1.4E-29 species lost per year with a lower loss rate. Even though the resulting loss of species due to entanglement remained the lowest of the impact categories, even after changing the loss rate, the relevance of including entanglement is considerable given that the marine environment is already exposed to impacts from climate change, ecotoxicity and eutrophication. Additionally, considering that the species lost due to entanglement was because of 0.1 g of lost gillnet from one vessel, the impacts at a larger scale could increase the number of species lost.

Applying the ReCiPe 2008 method and its associated indicators provided insights to where the environmental impacts occurred for each impact category at endpoint as well as which processes contributed to the effects. For the majority of the investigated impact categories, namely, global warming, freshwater ecotoxicity, freshwater eutrophication, terrestrial acidification, and terrestrial ecotoxicity the fishing activity and processes related to diesel to fuel the vessel represented the processes contributing the most to overall impacts. Impacts of marine ecotoxicity came from antifouling paint emissions. The environmental hotspot of this LCA study was global warming, due to high emissions of greenhouse gases because of fuel combustion in the vessel. Global warming led to 4.8E-09 species becoming lost each year.

This study represents a first test of the CF for entanglement and the quantification of marine debris in LCIA, however, there are inaccuracies within the data quality which leaves room for improvement. Regarding the datasets taken from Ecoinvent 3.8, more careful choices should be made. Furthermore, modelling the additional impact category of entanglement should be improved by assessing the impact pathway in Brightway2 to make full use of the software. Moreover, excluded processes in this study could be included in further research, such as vessel and engine production, ice production to maintain the quality of the fish onboard the boat, and the associated refrigerants. Requirements of fuel, fishing gear, antifouling, boat paint, and marine lubricating oil can be improved by communicating with stakeholders and fishers to get more accurate values. The location of where the loss occurred is important in terms of plastic and species density. As marine species are shown to be more sensitive to entanglement in areas where there are high densities of marine debris (Høiberg et al., 2022), and so further studies should explore the potential loss of species due to entanglement in lost fishing gear and test the CF in other locations than the one in this study.

Since LCA databases, for instance Ecoinvent, does not address plastics as pollutants to the biosphere, there is a need for developing datasets so that mismanaged plastics are considered emission flows. This would contribute to LCA studies incorporating plastic in their inventory as an emission. Furthermore, as the development of CFs for impact pathways such as entanglement and ingestion are progressing, potential effects from plastic pollution can be quantified and assessed at the impact assessment stage as well. Doing this, the knowledge base of plastic pollution in the marine environment increases, where the potential effects from plastic debris can be quantified and assessed.

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Appendices

Appendix 1: Sources of chosen Ecoinvent processes and datasets for the LCI.

Appendix 2: Detailed inventory of the activities and exchanges.

Appendix 3: Converting marine lubricating oil and boat paint from liter to kg.

Appendix 4: Calculations of the direct emissions occurring from fuel consumption in the vessel.

Appendix 5: Python script used for calculating results using Brightway2.

Appendix 6: Characterization factor (CF) for entanglement.

Appendix 7: LCA results at the midpoint level and endpoint using conversion factors for ReCiPe 2008, with a hierarchist perspective.

Appendix 1: Sources of chosen Ecoinvent processes and datasets for the LCI.

***A 1.1:** Overview of the datasets selected from the Ecoinvent 3.8 database. * = every biosphere flow reaches air as the environmental compartment.*

Technosphere inputs	**Ecoinvent 3.8 process**
Fuel for the vessel	"Diesel production, low sulphur, petroleum refinery operation"
Gillnet production	"Market for nylon 6"
	"Market for polyethylene, low density, granulate"
Maintenance vessel	"Market for alkyd paint, white, without solvent, in 60% solution state"
	"Market for lubricating oil"
	"Market for antifouling paint emissions"
Biosphere flows	**Ecoinvent 3.8 process**
Fishing activity	Carbon dioxide, fossil*
	Sulphur dioxide*
	Methane, fossil*
	Carbon monoxide, fossil*
	Nitric oxide*
	NMVOC, non-methane volatile organic compounds, unspecified origin*

Appendix 2: Detailed inventory of the activities and exchanges.

Activity	Fishing_activity						
Code	11ad99c5f1de4375a40cdffdf740a6df						
Location	GLO						
Reference product	Cod						
Type	Process						
Unit	kilogram						
Exchanges							
name	amount	database	location	unit	categories	type	Reference product
Carbon dioxide, fossil	0.4755	biosphere3		kilogram	air	biosphere	
Carbon monoxide, fossil	0.00044	biosphere3		kilogram	air	biosphere	
Methane, fossil	0.00003	biosphere3		kilogram	air	biosphere	
NMVOC, non-methane volatile organic compounds, unspecified origin	0.00036	biosphere3		kilogram	air	biosphere	
Nitric oxide	0.00656	biosphere3		kilogram	air	biosphere	
Sulfur dioxide	0.00017	biosphere3		kilogram	air	biosphere	
Fishing_activity	1	gillnets	GLO	kilogram		Production	Cod
Fuel_vessel	0.15	gillnets	GLO	kilogram		technosphere	Fuel
Gillnet_prod	0.0066	gillnets	GLO	kilogram		technosphere	Gillnets
Maintenance_vessel	0.000942	gillnets	GLO	kilogram		technosphere	Maintenance_vessel
Activity	**Fuel_vessel**						
Code	17f4a94df4684afb817b3312b19ef3c8						
Location	GLO						
Reference product	Fuel						
Type	Process						
Unit	kilogram						
Exchanges							
Name	amount	database	location	unit	categories	type	Reference product
Fuel_vessel	0.15	gillnets	GLO	kilogram		production	Fuel
Diesel production, low-sulfur, petroleum refinery operation	0.15	Ecoinvent 3.8	Europe without Switzerland	kilogram		technosphere	Diesel, low sulfur
Activity	**Gillnet_prod**						
Code	0388d18a12e744e39958d18528b10de4						
Location	GLO						
Reference product	Gillnets						
Type	process						
Unit	kilogram						
Exchanges							
Name	amount	database	location	unit	categories	type	Reference product
Gillnet_prod	0.0066	gillnets	GLO	kilogram		Production	Gillnets
Market for nylon 6	0.0054	Ecoinvent 3.8	RER	kilogram		technosphere	Nylon 6
Market for polyethylene, low density, granulate	0.0012	Ecoinvent 3.8	GLO	kilogram		technosphere	Polyethylene, low density, granulate
Activity	**Maintenance_vessel**						
Code	73d68d35cd6c42d3b7a37992e2b44daf						
Location	GLO						
Reference product	Maintenance_vessel						
Type	process						
Unit	kilogram						

Exchanges							
Name	amount	database	location	unit	categories	type	Reference product
Maintenance_vessel	0.000942	gillnets	GLO	kilogram		Production	Maintenance_vessel
market for alkyd paint, white, without solvent, in 60% solution state	0.000192	Ecoinvent 3.8	RER	kilogram		technosphere	alkyd paint, white, without solvent, in 60% solution state
market for antifouling paint emissions	-0.00003	Ecoinvent 3.8	GLO	kilogram		technosphere	antifouling paint emissions
market for lubricating oil	0.000072	Ecoinvent 3.8	RER	kilogram		technosphere	lubricating oil

Appendix 3: Converting marine lubricating oil and boat paint from liter to kg.

A 3.1: *Converting the process of marine lubricating oil and boat paint from liter to kg.*

Process	**Initial value in liter/ton fish**	**Value in kg/kg fish**	**Density**	**Calculation**
Marine lubricating oil	0.9	0.72	800 kg/m3 1m3 = 1000 L	$\frac{0.9\ \frac{l}{ton}}{1000\ \frac{l}{m3}} \times 800\ \frac{kg}{m3} = 0.72\,\frac{g}{kg}$
Boat paint	0.12	0.192	1.6 kg/L	$\frac{0.12\ \frac{l}{ton}}{1000\ \frac{l}{m3}} \times 1.6\ \frac{kg}{L} = 0.192\,\frac{g}{kg}$

Appendix 4: Calculations of the direct emissions occurring from fuel consumption in the vessel.

A 4.1: *Requirement of fuel consumption applied in this study.*

Fuel consumption in this study	Value	Unit
	0.15	kg

A 4.2: *Calculation of direct emissions occurring from fuel combustion in the vessel.*

Direct emissions of fuel combustion in vessel to atmosphere, air	**Calculation**	**Value**	**Unit**
CO_2	$3.17 \frac{kg}{kg\ fuel} \times 0.15\ kg\ fuel\ \times 1000$	475.5	g/kg
SO_2	$1.16 \frac{g}{kg\ fuel} \times 0.15\ kg\ fuel$	0.17	g/kg
CH_4	$0.23 \frac{kg}{ton\ fuel} \times 0.15\ kg\ fuel\ \times \frac{1000}{1000}$	0.03	g/kg
NOx	$43.76 \frac{kg}{ton\ fuel} \times 0.15\ kg\ fuel\ \times \frac{1000}{1000}$	6.56	g/kg
CO	$2.9 \frac{kg}{ton\ fuel} \times 0.15\ kg\ fuel\ \times \frac{1000}{1000}$	0.44	g/kg
NMVOC	$2.4 \frac{kg}{ton\ fuel} \times 0.15\ kg\ fuel\ \times \frac{1000}{1000}$	0.36	g/kg

Appendix 5: Python script used for calculating LCA results using Brightway2.

```
import os
import matplotlib.pyplot as plt
import numpy as np
import bw2data as bd
import bw2io as bi
import bw2calc as bc
import pandas as pd
from pathlib import Path
from warnings import warn
from functools import partial
from stats_arrays import *
from bw2calc.lca import *

bd.projects.set_current("casestudy_gillnet")

# Setup of biosphere data
bi.bw2setup()

# Importing Ecoinvent 3.8
dirpath = r"C:\Users\Sunniva\Documents\LCA\ecoinvent
3.8_cutoff_ecoSpold02\datasets"
ei = bi.SingleOutputEcospold2Importer(dirpath, "ecoinvent
3.8_cutoff_ecoSpold02")
ei.apply_strategies()
ei.all_linked
ei.write_database()
ei=bd.Database('ecoinvent 3.8_cutoff_ecoSpold02')

# Listing the available databases
bd.databases

# Importing excel file with activities and exchanges and linking it to
Ecoinvent
```

```
ex = bi.ExcelImporter("/Users/Sunniva/Documents/LCA/Inventory_cod_2.xlsx")

ex.apply_strategies()

ex.match_database(fields=('name', 'unit', 'location'))

ex.match_database("ecoinvent 3.8_cutoff_ecoSpold02", fields=('name', 'unit',
'location'))

ex.statistics()

ex.write_database()

ex=bd.Database('gillnets')

ex.register()


# List the LCIA methods available

list(bd.methods)

len(bd.methods)


# Finding ReCiPe hierarchist at midpoint

import random

suitable_methods = [m for m in bd.methods if 'ReCiPe Midpoint (H)' in str(m)
and not 'total' in str(m) and not 'w/o' in str(m)

        and not 'V1.13' in str(m) and not 'V1.13 no LT' in str(m) ]


print("Can use {} of {} LCIA methods".format(len(suitable_methods),
len(bd.methods)))

chosen_methods = random.sample(suitable_methods, 18)

print(chosen_methods)


# Getting activities from excel file

for node in bd.Database("gillnets").search("Fishing_activity"):

   print(node.id, node)

fishing = bd.get_activity(219694)

fishing


# Defining the functional unit

functional_unit = {fishing:1}


# Calculating LCA results for each midpoint category
```

```
result = {}

gillnet_lca = bc.LCA(functional_unit, chosen_methods[0])

gillnet_lca.lci()

gillnet_lca.lcia()

for category in chosen_methods:

  gillnet_lca.switch_method(category)

  gillnet_lca.lcia()

  result[category] = {}

  result[category]['score'] = gillnet_lca.score

  result[category]['unit'] = bd.Method(category).metadata['unit']

  print("The score is {:f} {} for impact category
{}".format(gillnet_lca.score,

                     bd.Method(category).metadata['unit'],

                     bd.Method(category).name)

   )


df = pd.DataFrame.from_dict(result).T

df


# The technopshere matrix

gillnet_lca.technosphere_matrix

print(gillnet_lca.technosphere_matrix)


# The biosphere matrix

gillnet_lca.biosphere_matrix

print(gillnet_lca.biosphere_matrix)


# The characterization matrix

lca.characterization_matrix

print(lca.characterization_matrix)


# The inventory

gillnet_lca.inventory

print(gillnet_lca.inventory)
```

```
# Table

gillnet_lca_unitProcessContribution =
gillnet_lca.characterized_inventory.sum(axis=0).A1

gillnet_lca_unitProcessRelativeContribution =
gillnet_lca_unitProcessContribution/gillnet_lca.score

gillnet_lca_unitProcessRelativeContribution


# Process contribution

%matplotlib inline

from bw2analyzer.matrix_grapher import SparseMatrixGrapher

from bw2analyzer import ContributionAnalysis

ca.annotated_top_processes(gillnet_lca, names=True, limit=0.001,
limit_type='percent')


# Top emissions contribution

ca.annotated_top_emissions(gillnet_lca, limit=0.02, limit_type='percent')
```

Appendix 6: Characterization factor (CF) for entanglement.

A 6.1: *Characterization factor (CF) for the loss of plastic off the coast of Tromsø in Norway. The development of this CF is done by Marthe Alnes Høiberg, as well as the conversion from PAF/m2 to species.year/kg plastic emitted.*

CF macroplastic debris entanglement developed by Marthe Alnes Høiberg		
Unit	Value	Comment
PAF/m2	3.01E-10	Average CF 1 year after a release of a plastic emission from the west coast of Tromsø.
PDF/m2	3.01E-10	Conversion step from PAF to PDF, assuming a 1:1 ratio as the effects of the stressor is expected to lead to mortality.
PDF/m3	3.01E-12	Conversion step from m2 to m3, taking 100 m as the average depth for continental area.
Species/m3	3.45E-12	Average species density per m3 in marine ecosystems (ReCiPe 2016).
Species.year/kg plastic emitted	1.04E-23	CF value for use with ReCiPe.

Appendix 7: LCA results at the midpoint level and endpoint using conversion factors for ReCiPe 2008, with a hierarchist perspective.

A 7.1: *Midpoint results using ReCiPe (H) 2008.*

Impact categories at midpoint using ReCiPe (H) 2008	**Unit**	**Value**
ReCiPe Midpoint (H) | agricultural land occupation | ALOP	square meter-year	9.1E-04
ReCiPe Midpoint (H) | climate change | GWP100	kg CO2-Eq	6.1E-01
ReCiPe Midpoint (H) | fossil depletion | FDP	kg oil-Eq	2.2E-01
ReCiPe Midpoint (H) | freshwater ecotoxicity | FETPinf	kg 1,4-DCB-Eq	8.0E-04
ReCiPe Midpoint (H) | freshwater eutrophication | FEP	kg P-Eq	7.0E-06
ReCiPe Midpoint (H) | human toxicity | HTPinf	kg 1,4-DCB-Eq	1.7E-02
ReCiPe Midpoint (H) | ionising radiation | IRP_HE	kg U235-Eq	3.5E-02
ReCiPe Midpoint (H) | marine ecotoxicity | METPinf	kg 1,4-DCB-Eq	8.9E-03
ReCiPe Midpoint (H) | marine eutrophication | MEP	kg N-Eq	1.7E-04
ReCiPe Midpoint (H) | metal depletion | MDP	kg Fe-Eq	2.9E-03
ReCiPe Midpoint (H) | natural land transformation | NLTP	square meter	2.1E-03
ReCiPe Midpoint (H) | ozone depletion | ODPinf	kg CFC-11-Eq	1.0E-07
ReCiPe Midpoint (H) | particulate matter formation | PMFP	kg PM10-Eq	3.2E-04
ReCiPe Midpoint (H) | photochemical oxidant formation | POFP	kg NMVOC	1.1E-03
ReCiPe Midpoint (H) | terrestrial acidification | TAP100	kg SO2-Eq	1.1E-03
ReCiPe Midpoint (H) | terrestrial ecotoxicity | TETPinf	kg 1,4-DCB-Eq	1.8E-05
ReCiPe Midpoint (H) | urban land occupation | ULOP	square meter-year	7.0E-04
ReCiPe Midpoint (H) | water depletion | WDP	cubic meter	8.6E-05

A 7.2: *Conversion factors from midpoint to endpoint level for ReCiPe 2008. Every factor is taken from the ReCiPe webpage, except for entanglement. Source: (The National Institute for Public Health and the Environment, 2017).*

Impact categories for ReCiPe 2008 at an endpoint level	**Unit**	**Value**
Global warming	Species.year/kg CO2 eq.	7.93E-09
Acidification – Terrestrial ecosystems	Species.year/kg SO2 eq.	1.52E-09
Toxicity – Terrestrial ecosystems	Species.yr/kg 1,4-DBC emitted to industrial soil eq.	1.51E-07
Eutrophication – Freshwater ecosystems	Species.year/kg P to freshwater eq.	4.44E-08
Toxicity – Freshwater ecosystems	Species.yr/kg 1,4-DBC emitted to freshwater eq.	8.61E-10
Toxicity – Marine ecosystems	Species.yr/kg 1,4-DBC emitted to sea water eq.	1.76E-10
Entanglement	Species.yr/kg plastic emitted	1.04E-23

The common formula for calculating the endpoint results in A 7.3 is:

$$midpoint\ result \times conversion\ factor\ =\ endpoint\ result$$

A 7.3: *Endpoint results using conversion factors from ReCiPe 2008.*

Impact categories at endpoint using ReCiPe (H) 2008	**Unit**	**Value**
Global warming	Species.year	4.84E-09
Acidification – Terrestrial ecosystems	Species.year	1.67E-12
Toxicity – Terrestrial ecosystems	Species.year	2.71E-12
Eutrophication – Freshwater ecosystems	Species.year	3.11E-13
Toxicity – Freshwater ecosystems	Species.year	6.89E-13
Toxicity – Marine ecosystems	Species.year	1.57E-12
Entanglement	Species.year	1.04E-27

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