Master's thesis

NTNU
Norwegian University of Science and Technology
Faculty of Engineering
Department of Energy and Process Engineering

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A life cycle assessment of Norwegian wild-caught cod with demersal trawl and set gillnet with a focus on plastic

Master's thesis in Industrial Ecology
Supervisor: Francesca Verones
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Abstract

The accumulation of marine plastic debris poses a growing threat to the oceans, resulting in the debilitation, mutilation, and mortality of millions of marine animals annually. The environmental threat can be linked to fishing gear, as a significant proportion is plastics. Norway, Europe's biggest fishery nation, has a sustainable focus and wishes to reduce marine littering. However, there is a significant knowledge and data gap regarding marine plastics and their impacts on Norwegian marine ecosystems, limiting Norwegian fisheries in achieving goals set by the United Nations.

Life cycle assessment is one well-established method to quantify products' impacts. However, it was initially developed to assess land-based products and lack impact categories focusing on marine ecosystems and drivers of marine biodiversity loss, such as plastic debris. As a result, the methodology misses adequate inventory data and impact assessment methods. This thesis assesses the Norwegian fishing fleet catching wild cod with a comparative LCA of two fishing gears, collecting inventory data for all relevant processes, including plastic flows, potentially reducing inventory gaps. Further, the thesis assesses newly developed characterization factors' impacts for macroplastic entanglement and tire wear microplastic emissions in marine ecosystems.

Inventory results highlight plastic flows, showing that trawl requires 77.17 grams and gillnet 56.84 grams per functional unit. Plastic loss to the marine environment is higher for trawl than gillnet, primarily driven by lost fishing gear and marine coating from vessels. Loss of trawl gear is 0.61 grams of micro and 0.27 grams of macroplastics per functional unit, while gillnet gear contributes 0.18 grams of micro and 0.36 grams of macroplastics. These key findings can provide significant insight into mitigation strategies addressing marine plastics, and the inventory could reduce inventory data gaps regarding plastic flows.

LCIA results at the midpoint and endpoint level showed that gillnet is the most beneficial catchment method for the assessed impact categories, except for entanglement. Tire wear was equal for both cases. These results are mainly due to gillnets lower fuel consumption and a smaller vessel per catch. The highest potential loss in species.yr was found in terrestrial impact categories, and categories assessing marine environments had low impacts in this thesis, emphasizing the need for additional LCIA methods and inventory links to the marine environment. Results for entanglement for trawl is 1.98E-22 species.yr and 2.60E-22 for gillnet. Tire wear is 5.86E-18 species.yr. The new characterization factors' potential impact is significantly smaller than established categories but entails high uncertainty and limitations.

The LCA study reveals a need for research and quantification on fishing gear, plastic loss to the ocean, marine coatings, final environmental compartments, and methodologies. Further, excluded processes, more gear types, species, and countries should be included in further studies. Closing these gaps will enhance the understanding of fishing activities and plastic's environmental impact, support mitigation strategies, and assist Norwegian fisheries in meeting goals set by the United Nations.

Sammendrag

Akkumulering av marine plast utgjør en økende trussel i havet, og medfører svekkelse, lemlestelse og død hos millioner av marine dyr årlig. Miljøtrusselen kan knyttes til fiskeredskaper, da en betydelig andel består av plast. Norge er Europas største fiskerinasjon, har et bærekraftig fokus, og ønsker å redusere marin forsøpling. Imidlertid er det betydelige kunnskaps- og datagap om marine plast og deres påvirkning på norske marine økosystemer, noe som begrenser norske fiskerier i å nå målene satt av FN.

Livssyklus analyse er en veletablert metode for å kvantifisere produkters miljøpåvirkning. Imidlertid ble metoden opprinnelig utvikler for å vurdere landbaserte produkter og mangler påvirkningskategorier med fokus på marine økosystemer og tap av marint biologisk mangfold, for eksempel plast. Som et resultat mangler metoden tilstrekkelig med livssyklusinventar og påvirkningskategorier. Denne masteroppgaven har analysert den norske fiskeflåten som fanger villtorsk med to fiskeredskaper, og samler inn data for alle relevante prosesser, inkludert plast, noe som potentielt reduserer mangler i livssyklusinventar. Videre vurderes effekten av nylig utviklede karakteriseringsfaktorene for makroplast innvikling og mikroplast fra dekkslitasje i marine økosystemer.

Resultatene fra livssyklusinventaret fremhever plast og viser at trål krever 77,17 gram plast per funksjonell enhet og garn 56,84 gram. Plasttap til det marine miljøet er høyere for trål enn for garn, hvor størst tap kommer fra fiskeredskap, etterfølgt maritim maling fra fartøyer. Tap av trålredskap er 0,61 gram mikroplast og 0,27 gram makroplast per funksjonell enhet, mens garnredskap mister 0,18 gram mikroplast og 0,36 gram makroplast. Funnene kan gi betydelig innsikt i tiltak for å håndtere marint plastavfall, og livssyklusinventaret kan redusere mangler i data om plast.

Resultatene fra livssyklusvurderingen på midt- og endepunktet viser at garn er den mest gunstige fangstmetoden for de vurderte påvirkningskategoriene, med unntak av innvikling. Slitasje fra dekk var lik for begge tilfeller. Resultatene skyldes hovedsakelig garnets lavere drivstofforbruk og mindre fartøy per fangst. Det høyeste potensielle tapet i antall species.yr ble funnet i påvirkningskategorier for landjord, og kategorier som vurderer marine miljøer hadde liten påvirkning i denne avhandlingen, noe som understreker behovet for ytterligere karakteriserinsfaktorer og koblinger til livssyklusinventar for marine miljøer. Resultatene for innvikling i trål er 1.98E-22 species.yr og 2.60E-22 for garn. Slitasje på dekk er 5.86E-18 species.yr. De nye karakteriseringsfaktorenes potensielle påvirkning er betydelig mindre enn etablerte kategorier, men medfører høy usikkerhet og begrensninger.

Livssyklusanalysen avdekker behovet for utliggere forskning og kvantifisering av fiskeredskaper, plasttap til havet, marin maling, faktisk miljø og metodologier. Videre bør ekskluderte prosesser, flere typer fiskeredskaper, arter og land inkluderes i nye studier. Å tette disse hullene vil forbedre forståelsen av fiskeriers og plast sin miljøpåvirkning, støtte tiltak for å redusere plast i havet og hjelpe norske fiskerier med å nå målene som er satt av FN.

Preface

It is with great pleasure and a sense of accomplishment that I present this master's thesis in Industrial Ecology, conducted at NTNU. First, I would like to express my gratitude to my supervisor Francesca Verones and co-supervisors, Marthe Alnes Høiberg and Philip Gjedde, whose guidance, expertise, encouragement, and insights have been invaluable in shaping this thesis. Furthermore, I would like to thank fellow students in Industrial Ecology, friends, and family for their support and motivation.

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3 List of Abbreviations

AB	Activity Browser
AoP	Areas of Protection
CF	Characterization factor
DF	Directorate of Fisheries
EVA	Ethylene vinyl acetate
FR	Fish requirement (3.25 kg)
FU	Functional unit
GHG	Greenhouse gas
GWP	Global warming potential
LCA	Life cycle assessment
LCI	Life cycle inventory
LCIA	Life cycle impact assessment
LR	Loss rate
MarILCA	Marine Impacts in LCA
PA	Nylon
PE	Polyethene
PES	Polyester
PLP	Plastic leak project
PP	Polypropylene
SDG	Sustainable Development Goals
SSB	Statistics Norway
SSD	Species Sensitivity Distribution
UN	United Nations
EF	Effect factor

1 Introduction

The ocean is a vital part of our planet, covering over two-thirds of its surface area (Vallis, 2012), and is home to diverse species such as plants, fish, birds, and marine mammals (McLeod & Leslie, 2009). The ocean has been a source of human food and livelihood for centuries, accounting for 19% of global animal protein intake in 2019 (FAO, 2022). Further, the ocean regulates Earth's climate, affecting global temperature and weather patterns by redistributing heat and clouds (Vallis, 2012) and mitigating climate change effects by acting as a carbon sink, absorbing about 25% of global CO_2 emissions. However, despite the ocean's essential role, it faces numerous threats from human activities, including ocean warming, eutrophication, acidification, overfishing, and the accumulation of marine pollution and plastic waste. These threats pose significant risks to marine ecosystems, the provision of marine ecosystem services, and the sustainability of the sea-based food chain (United Nations, 2022).

One of the most important ways humans utilize and threaten the ocean is through fisheries. For thousands of years, humans harvested global fish stocks sustainably. However, technological advancements, modern communication, and increased vessel movements in the second half of the 20th century altered the exploitation of fish stocks, resulting in the human fishing capacity to outpace fish growth and reproduction rates (Hilborn & Hilborn, 2012). As a result, in 2019, over 35% of global fish stocks were at biologically unstable levels due to overexploitation (United Nations, 2022). In addition to overfishing, human fishing activities harm the seabed. Bottom trawling has impacts comparable to clearcutting rainforests (Hilborn & Hilborn, 2012) and can crunch, bury and expose marine animals, further jeopardizing the oceans' biodiversity (Watling & Norse, 1998).

The accumulation of marine plastic debris is a growing threat in the ocean, and it can be closely linked to fisheries, as a large proportion of fishing gear is made of plastics (Syversen et al., 2020). Analyses of European beaches suggest that an average of 32% of marine litter originates from maritime sources, with approximately 65% of this attributed to fisheries (Eunomia, 2016). Estimations of globally dissipated fishing gear in 2018 showed an annual loss of about 50 000 tons (Kuczenski et al., 2021). These immense quantities of plastic litter in the ocean and its physical properties (durability and persistence) are of concern and directly and indirectly impact marine biota and habitats (GESAMP, 2021). Plastic litter can affect marine animals' ability to sense hunger, capture prey, digest food, reproduce, escape predators, and limit movement. In addition, microplastic ingestion can be a pathway for harmful chemicals (United Nations, 2012). Every year, millions of marine animals are debilitated, mutilated, and killed by marine debris (Butterworth et al., 2012), as they get entangled in or ingest plastic products such as fishing gear, lines, ropes, packaging, and bags (Butterworth et al., 2012). Abandoned, lost, or otherwise discarded fishing gear is pointed out as a marine litter that may impact marine biota and habitats more than other sources due to its purpose of catching marine animals and its composition of synthetic materials that does not degrade in seawater (GESAMP, 2021).

The importance of reducing marine pollution and sustainable utilization of the ocean's resources is recognized by the United Nations (UN) through sustainable development goal (SDG) number 14, *Life Below Water,* which aims to conserve and use ocean resources for sustainable development (United Nations, 2022). This is a central focus as global consumption of fish has seen a rapid increase of 122% from 1990 to 2018 (United Nations, 2022), and it is expected to keep growing, driven by population growth, health benefits, and its sustainable profile compared to land-based animal protein sources (Hallström et al., 2019). It is plausible that Norwegian fisheries will play a crucial role in delivering to this demand. Fisheries have historically been vital for the Norwegian economy and settlement (FAO, 2013), and Norway is today Europe's biggest fishery nation and the world's 9th most extensive (Fiskeridirektoratet, 2021). Moreover, the Norwegian fishing fleet has sustainable fishing as a focus area and intends to reduce marine littering (Fiskeridirektoratet, 2022a). However, to achieve SDG number 14, Norwegian fisheries must close the current knowledge- and data gap concerning marine plastics and their impacts on (Norwegian) marine ecosystems, and to achieve this goal, approaches to evaluate Norwegian fisheries and plastics' impact on the marine environment are crucial.

One well-established method to quantify impacts of manufactured and consumed products is life cycle assessment (LCA). The method describes resource use through a product's life cycle and potential environmental consequences. The method can compare products, identify tradeoffs and problem-shifting, inform decision-makers, and be used for marketing (ISO, 2006). However, LCA was originally developed to assess land-based products, focusing on impacts on terrestrial and freshwater ecosystems, and lack impact categories focusing on marine ecosystems and drivers of marine biodiversity loss (Woods et al., 2016). One of the drivers lacking is plastic debris in the marine environment. The methodology misses adequate inventory data on plastic loss and established life cycle impact assessment (LCIA) methodologies on plastic impacts (Maga et al., 2021). One of the initiatives to close the mentioned methodological gap in LCIA is the establishment of the Marine Impacts in LCA (MarILCA) working group. They aim to develop LCIA methods on plastic emissions and marine impacts. Inventory modeling and quantifying plastic leakage to the biosphere are not a part of MarILCA. However, they are working closely with the Plastic Leak Project (PLP), which has made the first steps of a plastic leakage assessment (Boulay et al., 2021). Indicators are currently being developed and published to close the LCIA methodology gap, for instance, with the effect model for macro plastic entanglement (Høiberg et al., 2022), a combined effect and exposure factor of microplastics in freshwater and marine ecosystems (Lavoie et al., 2021) and a simplified characterization factor (CF) for tire wear microplastic emissions (Corella Puertas et al., 2022).

This thesis will contribute to the work by assessing the Norwegian fishing fleet catching wild cod with a comparative LCA of two fishing gears, demersal trawl and set gillnet. The assessment is based on cod as it was the species with the highest catch value in 2021, with 29.9% of the total catch, and the second biggest in mass, with 14.7%, only beaten by Norwegian spring pawn herring (Fiskeridirektoratet, 2022b). Fishing gear was selected as demersal trawl accounted for 31,5% of the total cod catch in mass, and sett gillnet 21.4% (Fiskeridirektoratet, 2022e). A life cycle inventory (LCI) of all relevant processes has been collected, including macro and microplastic. Further, the thesis aims to assess the impacts of the newly developed CF for marine plastics, as well as established LCIA methods at midpoint and endpoint level, such as climate change, eutrophication, ecotoxicity and acidification.

2 Method

In the fall of 2022, a project thesis was conducted to learn about the Norwegian seafood industry and how previous LCA studies have assessed seafood products. Further, the project aimed to specify system boundaries and a functional unit (FU), quantify all relevant processes and establish an LCI (Sterri, 2022). However, LCA is an iterative method, and as more is understood regarding the given system, new data points, requirements, or limitations may be identified, altering the goal and scope (ISO, 2006). Consequently, this thesis continued the inventory work with further iterations, resulting in modifications to the system boundary, FU, and LCI. In addition, this thesis includes the last steps of an LCA with the LCIA phase and new interpretations. The *method* section describes work from the preliminary project thesis, changes made with new iterations, and the LCIA methodology and software.

2.1 Goal and scope definition

The goal and scope definition is the first phase of an LCA study and sets the basis for the assessment (ISO, 2006). This thesis aims to quantify all relevant processes of the Norwegian seafood industry catching wild cod, focusing on fishing gear and mismanaged plastic. Further, the thesis will address how plastic loss due to cod fishing in Norway impacts the marine environment with the newly developed CFs.

Further, setting the FU is essential to defining and quantifying the final product. It is necessary for comparing results on a shared basis, and it provides a reference for the input and output data in the system (ISO, 2006). Therefore, to select an appropriate FU, LCA studies on seafood products were assessed as part of the preliminary work. FU of seafood products depend highly on the study's goal and its system boundaries (Vázquez-Rowe et al., 2012), but the main result showed that most LCA studies used a FU of 1 kg or 1 ton catch landed in the port (Sterri, 2022). The FU used in this thesis was selected based on the FU by Loubet et al. (2021), a French inventory of the seafood supply chain focusing on plastic loss, to compare the results of that study to the current. Therefore, the selected FU in this thesis is one kilogram of wild-caught cod filets without skin and bones transported to the wholesaler/consumer.

Lastly, describing the system boundary is important for the goal and scope definition, as it specifies the unit processes included in the product system (ISO, 2006). This thesis limits the system to wild-caught cod fished by Norwegian commercial fisheries in the Norwegian fishing zone. The assessment is further limited by gear type, to either cod caught with the demersal trawl or the set gillnet. The two gear types lead to differences between the two systems due to differences in fishing method, material input to fishing gear, vessel sizes, distance moved by vessel and average gear loss. Details are further explained in *Section 2.2 Life cycle inventory.* The processes included in the system boundary are shown in *Figure 1.*

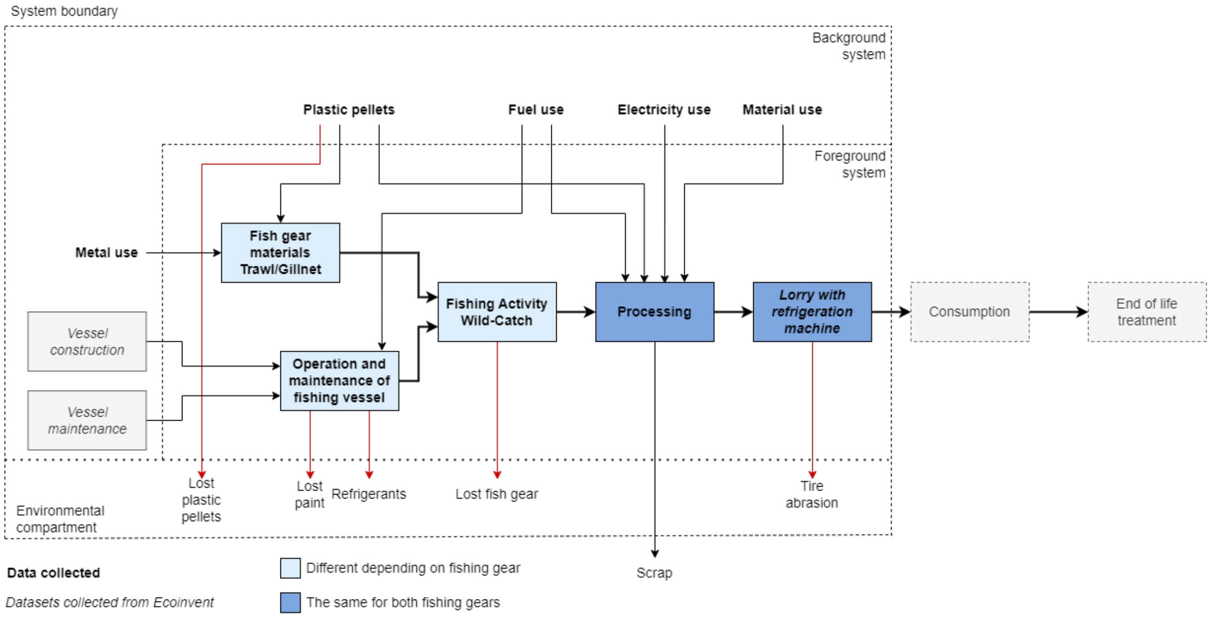


Figure 1 System boundary of the assessed system. Black arrows represent exchanges within the technosphere, and red arrows exchange from the technosphere to the biosphere. Light blue processes illustrate differences depending on fishing gear, and dark blue illustrate that processes are identical for both cases.

Figure 1 illustrates the processes of capturing wild cod with the two selected gear types. The first process is *Fishing gear materials* and includes inputs from the technosphere of plastic pellets and metals. Other inputs concerning the production of gear and its transportation are out of scope in this thesis. The next phase is the *operation and maintenance of the fishing vessel*. This process has two inputs collected from Ecoinvent: *vessel construction* and *vessel maintenance* (further explained in *section 2.2.2*). In addition, the process contains inputs of fuel use and outputs to the environment of paint and refrigerants. The third process is *fishing activity*. During this phase, gear is exposed to wear and tear, leading to exchanges of plastic fragments from the technosphere to the natural environment. *Processing* includes inputs of plastic pellets and fuel-, electricity- and material use. Outputs of scrap are outside the scope. *Transportation* includes a dataset collected from Ecoinvent (further explained in *section 2.2.5)* and the loss of tire abrasion. *Consumption* and *End-of-life treatment* is outside the scope as this is the same for both cases, and loss of plastic is minor (further explained in *section 4.1).*

This assessment assumes the following simplifications:

- No by-catch during fishing activity.
- No loss of other plastic products or mismanaged plastic waste onboard vessels.
- No fish is processed onboard the vessel. It is processed onshore for human consumption.
- No loss of edible products during transportation.
- No microplastic loss from road marking, other vehicles, and road products.
- No loss of other materials than plastic, for instance steel in fishing gear.
- 100% of lost fishing gear ends in the ocean as its environmental compartment and gear retrieval is considered 0%.
- Plastic in vessel construction is not considered when addressing plastic loss.

2.2 Life cycle inventory

The second phase of an LCA is the LCI, aiming to collect and calculate quantifiable input and output data on a system throughout its life cycle to meet the study's goal (ISO, 2006). It makes LCA a data-intensive methodology, and primary data collection is time-consuming and costly. Therefore, collection efforts in LCA are commonly focused on specific activities, reflecting the assessment's focus (foreground system), and the remaining activities (background system) are modeled with generic data from LCI databases (Wernet et al., 2016).

Ecoinvent is the largest transparent unit-process database for LCI worldwide, with global databases and regionalized LCIAs (Wernet et al., 2016). This assessment has used activities with the cut-off approach from version 3.9.1, the newest release (December 2022), correcting issues, improving documentation, and updating emission factors (Ecoinvent, 2022). The cut-off approach is one of several ways to model allocation. It is an attributional approach dealing with recycling/end-of-life allocation. It decides if the first or second life cycle is allocated the benefit and burden of the recycling process (Williams & Eikenaar, 2022).

The following section describes the data collection and datasets used to cover the assessment's needs.

2.2.1 Fishing gear materials

The European Commission categorizes fishing gear into three types: towed gears (trawls and dredges), passive gears (gillnets, trammel nets, longlines, and handlines), and intermediate mobile gears (seines, towed longlines, and trolling lines). The environmental impact connected to fishing gear varies greatly with gear type, depending on its physical characteristics, operation, timing, location, and extent of its use. Gears that significantly impact one environmental impact category may have a lower rank in another (Gascoigne & Willsteed, 2009), making a comparative LCA of two different gear types for several impact categories interesting. Therefore, it was decided to assess and compare a towed gear (active gear) and a passive gear. This section describes the selected gear types and their material composition.

Active gear – Demersal trawl: Active fishing gears are moved through a relatively large area by vessels to capture fish quickly (Portt et al., 2006). Of the active gears used by Norwegian fisheries in 2021, the demersal trawl had the highest catch value of cod with 118 658 tons (Fiskeridirektoratet, 2022e) and was selected as the active gear type in this thesis. *Figure 2* illustrates the trawl net dragged along the seabed, capturing fish while water filters through its meshes. Along with the trawl net, the demersal trawl consists of a rockhopper in contact with the seabed and bullets on the upper side, creating buoyancy. Trawl doors on each side open the trawl, and wires connect them to the vessel. Additionally, the trawl net is protected from damage by structures on the seabed by a safeguarding layer known as *Labbetuss* (Syversen et al., 2020).

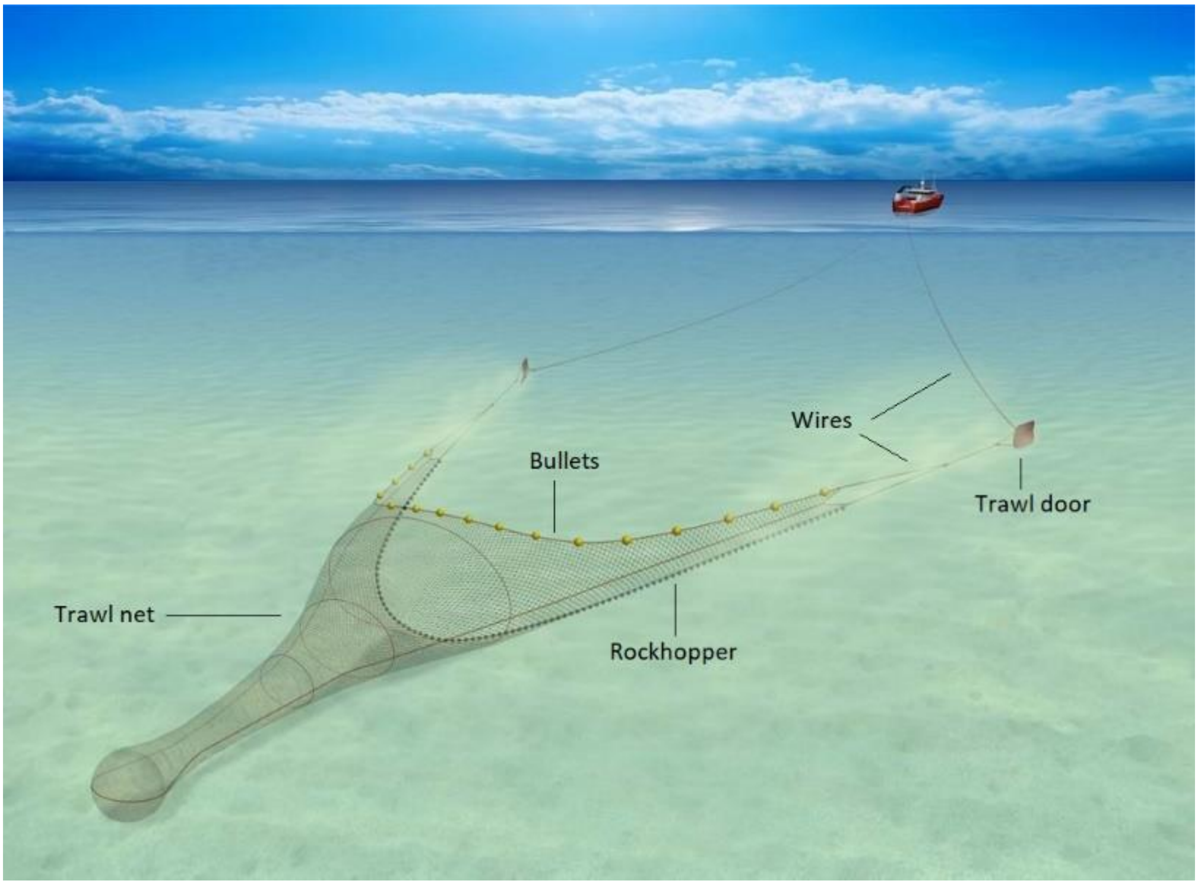


Figure 2 Vessel towing a demersal trawl along the seabed (Seafish, n.d.)

The trawl's material composition is derived from a 75-meter-long French bottom pair trawl used for benthic trawling in the North Sea, comprising 5500 kg of polyethylene (PE), 3800 kg of synthetic rubber, 380 kg of ethylene vinyl acetate (EVA), and 5934 kg of steel (Loubet et al., 2021). Syversen et al. (2020) have quantified wear and tear on fishing gear used in Norway. As a part of their work, fishing gear suppliers informed them that a trawl's average lifespan is 6-8 months and that approximately half of the trawlers in Norway utilize two trawls (Syversen et al., 2020). Therefore, a lifetime of 7 months and 1.5 trawls per vessel are used in this thesis. Data presented in *Table 1* have been used to estimate input from the technosphere per FU, which are presented in *Table 2* with the calculation method.

Table 1 Data collected on the demersal trawl, including material, weight, lifetime, and trawls per vessel.

Parameters	Values	Unit	References
Ethylene vinyl acetate	380	kg	(Loubet et al., 2021)
Polyethylene	5500	kg	(Loubet et al., 2021)
Synthetic rubber	3800	kg	(Loubet et al., 2021)
Steel	5934	kg	(Loubet et al., 2021)
Lifetime	7	months	(Syversen et al., 2020)
Trawls per vessel	1.5	trawls/vessel	(Syversen et al., 2020)

Table 2 Input from the technosphere per FU for demersal trawl with Ecoinvent datasets, values, and calculation method. FR = fish requirement (3.25kg).

Input from technosphere	g/FU	Formula
ethylene vinyl acetate copolymer production, RER	0.96	$\frac{Material\ weight}{An.catch\ pr\ vessel^{a} \cdot Lifetime} \cdot FR^{b} \cdot Trawls\ pr\ vessel$
polyethylene production, high density, granulate, RER	13.95	
synthetic rubber production, RER	9.63	
metal working, the average for steel product manufacturing, RER	15.05	

[a] Annual catch per vessel is further presented in *section 2.2.2 Vessel operation and maintenance.*

[b] FR = Fish requirement (3.25 kg), presented in *section 2.2.4 Processing*

Passive gear – Set gillnet: Passive fishing gears capture fish at specific locations over long periods with stationary gear fish swim into themselves (Portt et al., 2006). Of passive gears used by Norwegian fisheries in 2021, the set gillnet had the highest catch value of cod with 80 590 tons (Fiskeridirektoratet, 2022e) and is therefore selected as the passive gear type.

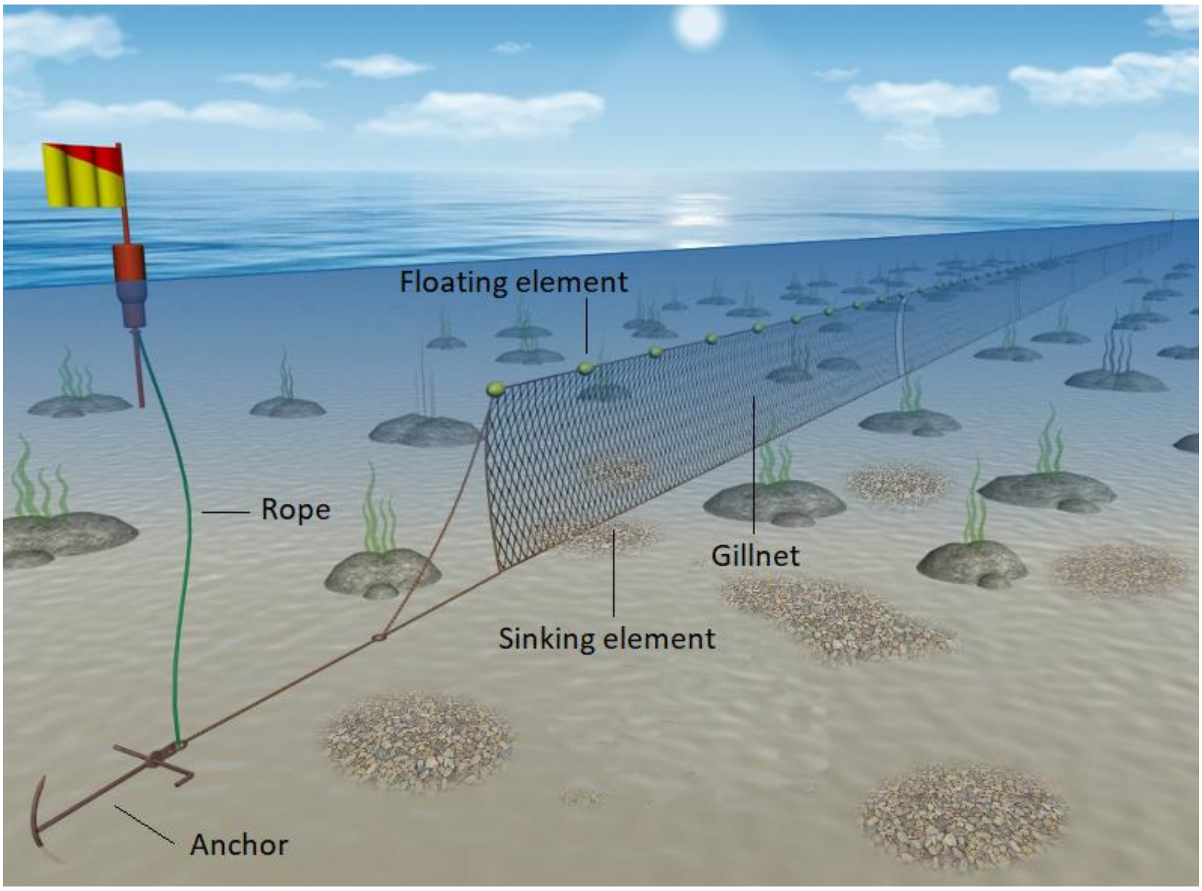


Figure 3 Set gillnet on the seabed (Cornwall good seafood guide, n.d.)

Figure 3 displays the elements in a gillnet, including the net, floating elements, sinking elements, rope, and anchors at both ends. Several factors, such as the target species, location, vessel size, and depth, determine the type of gillnet utilized during the fishing activity (Syversen et al., 2020). According to Syversen et al. (2020), who have information from gillnet producers and fishermen, a typical gillnet vessel uses 200 nets and 2000 meters of rope. Further, they state the gillnet compartments' weight, material composition and lifetime. This information and some assumptions are used for the data background for the set gillnet and are presented in *Table 3.* The lifetime of a gillnet varies widely and is determined by usage level, seabed conditions, and ocean currents. Some vessels replace 1000 nets annually, while others use the same net for 4-5 years (Syversen et al., 2020). In this thesis, the lifetime is assumed to be two years. The floating elements' material fraction is assumed to be 75% polypropylene (PP) and 25% polyethylene (PE). The upper portion of the rope is designed to sink and avoid boats and is made of polyester (PES), while the lower part is made to float and avoid seabed damage and is made of a mixture of PP and PE (Syversen et al., 2020). The material composition of the rope is assumed to be 50% PES, 25% PP, and 25% PE. The anchor weighs 20-120 kg and is typically made of stone, dregs, or patent iron (Syversen et al., 2020). One anchor is assumed to weigh 70 kg and to have a lifetime of 20 years. *Table 4* shows inputs from the technosphere per FU for set gillnet.

Table 3 Data collected on the set gillnet, including materials, weight, lifetime, and units per vessel.

Parameters		Values	Unit	References or assumptions
Sinking, floating, and nets per vessel		200	units	(Syversen et al., 2020)
Rope per vessel		2000	meter	(Syversen et al., 2020)
Anchor per vessel		400	units	(Syversen et al., 2020)
Net	Nylon	2.20	kg/unit	(Syversen et al., 2020) (Deshpande et al., 2020)
	Lifetime	2	years	Assumption
Sinking element	Lead	7.90	kg/unit	(Syversen et al., 2020)
	Weight of plastic	2.00	kg/unit	(Syversen et al., 2020)
	Polypropylene	1.50	kg/unit	Assumption: 75% of plastic weight
	Polyethylene	0.50	kg/unit	Assumption: 25% of plastic weight
	Lifetime	15	years	(Syversen et al., 2020)
Floating element	Weight of plastic	2.75	kg/unit	(Syversen et al., 2020)
	Polypropylene	2.06	kg/unit	Assumption: 75% of plastic weight
	Polyethylene	0.69	kg/unit	Assumption: 25% of plastic weight
	Lifetime	20	years	(Syversen et al., 2020)
Rope	Weight of plastic	87.50	mg/meter	(Syversen et al., 2020)
	Polyester	43.75	mg/meter	Assumption: 50% of plastic weight
	Polypropylene	21.88	mg/meter	Assumption: 25% of plastic weight
	Polyethylene	21.88	mg/meter	Assumption: 25% of plastic weight
	Lifetime	22.50	years	(Syversen et al., 2020)
Anchor	Stones, drags, or patent iron	70.00	kg/unit	(Syversen et al., 2020)
	Lifetime	20	years	Assumption

Table 4 Input from the technosphere per FU for set gillnet with Ecoinvent datasets, values, and calculation method. FR=Fish requirement (3.25 kg).

Input from technosphere	g/FU	Formula
polypropylene production, granulate, RER	0.70	$\frac{Material \cdot Units\ pr\ vessel}{An.catch\ pr\ vessel^{a} \cdot Lifetime} \cdot FR^{b}$
polyethylene production, high density, granulate, RER	0.26	
primary lead production from concentrate, GLO	1.74	
nylon 6-6 production, RER	3.63	
polyester fibre production, finished, RoW	0.06	
gravel and sand quarry operation, RoW	23.07	

[a] Annual catch per vessel, presented in section 2.2.2 Vessel operation and maintenance.

[b] FR = Fish requirement (3.25 kg), presented in *section 2.2.4 Processing*

2.2.2 Vessel operation and maintenance

Cod fishing with the demersal trawl and set gillnet require two different vessels: ocean vessels and coastal vessels. Coastal vessels comprise small vessels ranging from 10-20 meters, with a crew of 1-5 fishers. Ocean vessels are longer than 28 meters, have a crew of over 20 people, and are generally known for fishing in deeper waters (Deshpande et al., 2019). Vessel lengths are confirmed by the Norwegian Directorate of Fisheries (DF) statistics of catch, gear type, and vessel length for 2021. It shows that cod caught with demersal trawls were fished with vessels exceeding 28 meters, and for set gillnet, over 75% were caught by vessels under 14.99 meters (Fiskeridirektoratet, 2022c). Construction, maintenance, fuel use, and refrigerants required by the two vessel types are described in the following sections. A data source used for this purpose is Winther et al. (2020), who quantified the greenhouse gas (GHG) emissions of 21 Norwegian seafood products in 2017 as a collaboration between Sintef Ocean AS, Asplan Viak As, and RISE Research Institute of Sweden (Winther et al., 2020).

Construction: The construction of fishing vessels is typically not one of the significant climate aspects in LCAs of fisheries (Winther et al., 2020). However, the vessels for the two cases are different. Therefore, vessel construction is included but simplified based on the vessel's lightweight (weight of vessels without cargo, fuel, freshwater, storage, passengers, etc.) and annual catch per vessel. Background information for both vessels is from the Ecoinvent dataset *Trawl construction, steel, GLO,* based on a 1000 kg lightweight steel trawl from Peru with a 30-year lifetime. It has been extrapolated to the global market and includes materials, chemicals, energy, and the provision of materials and work (Avadi, 2018a).

Trawl: Vessel construction for a trawler is based on estimations of Ulstein's shipyard of approximately 3500 (2 770 – 4 700) tons lightweight per trawler and their assumed material composition of 90% low alloyed steel and 10% chrome steel (Winther et al., 2020). Statistics from the DF's presents annual catch for species and gear type and licenses and permits. Their data from 2021 show that 36 Norwegian vessels had cod trawling licenses and that 109 vessels had permits for trawling in the North Sea for multiple species (Fiskeridirektoratet, 2022f). However, this assessment assumes that only vessels with cod trawling licenses caught cod with demersal trawls due to lacking data on the species North Sea trawlers catch.

Set gillnet: Unfortunately, databases and information on gillnetting vessels' average weight and material composition are lacking. Due to this, and construction's relatively minor impact, the mentioned dataset is assumed to be a reasonable proxy for constructing a coastal vessel. However, the lightweight is downsized as the vessel's dimensions are smaller. A typical coastal vessel is 10-15 x 5 meters, while the median trawl in Ulstein's shipyard is 65-75 x 17 meters (Ulstein, n.d.). It is therefore assumed that a coastal vessel is 1/20 the weight of a trawl, giving a lightweight of 175 tons.

The exact number of vessels in the Norwegian fleet fishing cod with set gillnet is unavailable. Estimates are based on the DFs data on participation access and annual catch. In 2021, annual permits in various fisheries in the coastal fishing fleet were given to nine vessels catching cod south of 62 degrees and 1424 permits to vessels north of 62 degrees, allowing the catch of cod, haddock, and saithe (Fiskeridirektoratet, 2022f). However, the data does not specify the fishing gear used. Data on how much fish the gear types caught in 2021 were used to estimate vessels catching cod with set gillnet. Calculations led to 409 vessels and are further explained in *Appendix 1. Table 5* summarizes the collected data, and *Table 7* shows values per FU.

Table 5 Data collected on trawlers and coastal vessels.

Parameters	Value	Unit	References and assumptions
Lightweight trawler	3 500	ton	(Winther et al., 2020)
Lightweight coastal vessel	175	ton	Assumption
Lifetime	30	years	(Avadi, 2018a)
Cod trawler licenses	36	licenses	(Fiskeridirektoratet, 2022f)
Coastal vessels with gillnet	409	licenses	Assumption
Cod caught with demersal trawl	118 658	ton/year	(Fiskeridirektoratet, 2022c)
Cod caught with set gillnet	80 590	ton/year	(Fiskeridirektoratet, 2022e)

Maintenance: General maintenance, replacement, and repair are regularly performed on vessels to avoid unforeseen downtime or malfunction (Pillay et al., 2001). It has environmental impacts connected to it and is therefore included in this assessment. Maintenance for both cases is based on the dataset *trawl maintenance, steel, GLO* from Ecoinvent. The dataset embodies the maintenance required per 1000 kg steel trawl annually, including materials and work (Avadi, 2018b).

The dataset contains information that 91 kg of alkyd paint is needed annually to maintain the vessel (Avadi, 2018b). Marine paints smoothen surfaces, mitigate biofouling, and protect vessels from corrosive factors, including seawater, weathering, and wave action (Lusher & Olsen, 2021). Marine paints contain microplastics to ensure the stated criteria, enhance colors, improve resistance, and increase hardness (Carsten et al., 2015). Loss of these microplastics to the environment is not included in the Ecoinvent dataset and is therefore added manually. The Organization for Economic Cooperation and Development (OECD) estimates that 1.8% of marine coatings are lost to the ocean when initially added, 1% due to weathering, and 3.2% at end-of-life during removal and fugitive losses (OECD, 2009). In a Norwegian assessment of microplastic loss to the marine environment, Sundt et al. (2014) doubled the loss by OECD due to Norwegian conditions and lacking disposal options during maintenance. Further, the assessment used a polymer content of 25% in marine coatings, as data were unavailable from Norwegian paint manufacturers (Sundt et al., 2014). The same is used in this thesis and is presented in *Table 6*.

Fuel use: Fossil fuels in fisheries dominate their environmental impacts and can be linked to over 80% of their GHG emissions. The emissions are coupled with fuel efficiency in relation to catch (Winther et al., 2020) and are closely affected by gear type, fishing practices, operational techniques, distance to the fishing ground, vessel design, vessel age, and target species (Schau et al., 2009). Therefore, several fuel use coefficients were collected. Winther et al. (2020) are the most current and reliable source found for Norwegian fisheries and have been used for this thesis. Winther et al. (2020) calculated fuel consumption based on information received from the DF and determined fuel consumption for cod trawlers as 0.35 (0.22-0.51) liter fuel per kg live weight catch and 0.09 (0.02-0.17) for conventional coastal vessels. Both vessels typically utilize Norway's marine gas/diesel oil (Winther et al., 2020). Background data on fuel production are collected from the Ecoinvent dataset *diesel production, petroleum refinery operation, Europe without Switzerland.* The dataset includes crude oil entering the refinery, wastewater treatment, freshwater supply, refinery infrastructure, crude oil, storage on the ground, and energy provision. The activity ends with refined petroleum products (Brunner, 2017). Emission factors for marine gas oil/diesel usage are based on the Norwegian national emissions inventories by Statistics Norway (SSB) (SSB, 2016). When converting liters of diesel to kg of diesel, a density of 0.84 kg per liter was used (Winther et al., 2020). Collected data are presented in *Table 6*.

Refrigerant: Refrigerants are cooling substances used in refrigeration- and freezing systems onboard fishing vessels. However, due to international regulations, refrigerants with high climate emissions have, in recent years, been phased out. The regulations affect refrigerants with a high global warming potential (GWP) or ozone depletion (R22, chlorofluorocarbons (CFCs), hydrochlorofluorocarbons (HCFCs) and hydrofluorocarbons (HFCs)) (Winther et al., 2020). Winther et al. (2020) estimated refrigerant loss rates for four types of fishing vessels based on experienced refrigeration system workers, transportation with refrigeration, reports, SSB, and their previous work. The emission rate for a demersal trawler was estimated to be 0.007 kg HFC per ton landed and 0.008 for coastal purse seines (Winther et al., 2020). The coastal pure seines are used for the coastal vessel with gillnet. *Table 6* shows the collected data.

Table 6 Data collected on fuel use, maintenance, and refrigerant for both vessel types.

Parameters	Values	Unit	References
Alkyd paint	91	kg/year	(Avadi, 2018b)
Polymer content in paint	25	%	(Sundt et al., 2014)
Marine coating losses to water	12	%	(Sundt et al., 2014)
Fuel consumption cod trawl	0.35	l fuel/kg catch	(Winther et al., 2020)
Fuel consumption conventional coastal vessel	0.09	l fuel/kg catch	(Winther et al., 2020)
CO_2	3.17	kg/kg fuel	(SSB, 2016)
SO_2	1.156	kg/ton fuel	(SSB, 2016)
CH_4	0.23	kg/ton fuel	(SSB, 2016)
NOx	43.76	kg/ton fuel	(SSB, 2016)
CO	2.9	kg/ton fuel	(SSB, 2016)
NMVOC	2.4	kg/ton fuel	(SSB, 2016)
Emission rate HFC, demersal trawler	0.007	kg HFC/ton catch	(Winther et al., 2020)
Emission rate HFC, coastal purse seine	0.008	kg HFC/ton catch	(Winther et al., 2020)

Table 7 shows the datasets from Ecoinvent with amounts per FU and the calculation method used to calculate inputs and outputs for the case with demersal trawl and set gillnet.

Table 7 Input from technosphere and emissions to biosphere per FU for demersal trawl and set gillnet with Ecoinvent datasets, values, and calculation method. FR = Fish requirement (3.25 kg), LR = loss rate.

	Trawl	Gillnet	
Input from technosphere	g/FU	g/FU	Formula
trawl construction, steel, GLO	115.04	96.14	$\frac{Light\ weight\ vessel}{An.catch\ pr\ vessel^{a} \cdot Lifetime} \cdot FR^{b}$
trawl maintenance, steel, GLO	115.04	96.14	
diesel production, petroleum refinery operation, Europe without Switzerland	960.00	250.00	$Fuel\ consumption \cdot FR^{b}$
Emissions to biosphere	g/FU	g/FU	Formula
Microplastic	0.31	0.26	$Paint\ an.maint^{c} \cdot Polymer\ cont^{d}. \cdot LR^{e}$
Carbon dioxide, fossil (air)	3028.94	778.87	$Emission\ factor \cdot Fuel\ use$
Sulfur dioxide (air)	1.10	0.28	
Methane, fossil (air)	0.22	0.057	
Nitric oxide (air)	41.81	10.75	
Carbon monoxide, fossil (air)	2.77	0.71	
NMVOC, non-methane volatile organic compounds (air)	2.29	0.59	
Ethane, 1,1,1,2-tetrafluoro-, HFC-134a (air)	0.023	0.026	$Refrigerant\ emission\ rate \cdot FR^{b}$

[a] Annual catch per vessel.

[b] FR = Fish requirement (3.25 kg), presented in *section 2.2.4 Processing*.

[c] Paint required for annual maintenance.

[d] Polymer content in paint.

[e] Loss rate - paint to the marine environment.

2.2.3 Fishing activity

During fishing activities, gear and equipment are lost to the marine environment due to seabed damage or friction with hauling equipment during regular use (Syversen et al., 2020) or due to degradation caused by UV radiation/photodegradation, biodegradation, and thermal oxidative degradation (Andrady, 2011). Equipment is known to be lost or discarded, but the quantities reported in literature vary. For instance, Standal et al. (2020) state that The Norwegian Environment Agency estimates an annual loss of gillnets at 13 700 and that the DF refers to a number somewhere around 1000. With varying and limited data regarding loss of fishing gear and plastic loss from fishing gear, this section entails data uncertainties, further explained in *section 4.6*.

This thesis annual plastic loss from fishing gear is based on Syversen et al. (2020) and Alnes (2022). Syversen et al. (2020) provide information on the plastic loss caused by gear usage from nine gear types, including demersal trawl and set gillnet. Their numbers do not include material size, but they state that most lost material is microplastic. However, some larger fragments due occur. In addition, their assessment does not include lost equipment, which is also a significant source of plastic pollution in the ocean. Due to these limitations, data from the master thesis by Alnes (2022) was incorporated. The thesis quantifies annual plastic loss from six Norwegian fishing gears using material flow analysis, and data from literature, sales numbers, waste companies, and collected equipment. This thesis assumes Syversen et al. (2020) present microplastic loss and Alnes (2022) macroplastic loss.

Demersal trawl: Syversen et al. (2020) account for plastic loss from the two parts most exposed to wear and tear; the rockhopper and the protective mat (the Labbetuss*)*. The rockhopper comprises 2 205 kg discs and 782 kg fill pieces, typically made of dump truck tires with 66% synthetic rubbers and 34% natural rubber (Syversen et al., 2020). However, in this thesis, the material composition is assumed to be 100% synthetic. The rockhopper's parts are typically replaced when the span decreases or the filler pieces get porous. The lifetime varies from six months to 1.5 years, with a base case of ten months, and plastic loss range from 5-40% for discs and 5% for filler pieces (Syversen et al., 2020). For this thesis, the loss rate for discs is assumed to be 20%. The Labbetuss consists of thick PE ropes, which is frequently exposed to wear and tear, and therefore replaced regularly. In contact with three suppliers, Syversen et al. (2020) learned that the entire mat is replaced every six months. The mat weighs 40 kg per unit and has a material loss rate of 30-70%, with a base case of 50% (Syversen et al., 2020). Their study does not include plastic loss from the trawl net, which is another reason to include the loss rates from Alnes (2022). The loss rate for trawl in 2020 is estimated to be 84.6 g plastic per ton catch with a material composition of 9% PA, 12% PP, and 79% PE (Alnes, 2022). The collected data on plastic loss from demersal trawl is summarized in *Table 8.*

Table 8 Data collected on plastic loss from the demersal trawl.

Parameters		Value	Unit	References or assumptions
Rockhopper	Lifetime	10	months	(Syversen et al., 2020)
	Synthetic rubber	100	%	Assumption
- Filler pieces	Weight	782	kg/unit	(Syversen et al., 2020)
	Loss rate	5	%	(Syversen et al., 2020)
- Discs	Weight	2 205	kg/unit	(Syversen et al., 2020)
	Loss rate	20	%	Assumption
Labbetuss	Polyethylene	40	kg/unit	(Syversen et al., 2020)
	Lifetime	6	months	(Syversen et al., 2020)
	Loss rate	50	%	(Syversen et al., 2020)
Macro plastic	Plastic loss	84.6	g/ton catch	(Alnes, 2022)
	Nylon	9	%	(Alnes, 2022)
	Polypropylene	12	%	(Alnes, 2022)
	Polyethene	79	%	(Alnes, 2022)

Set gillnet – plastic loss: Gillnets are exposed to wear and tear when pulled into the boat, and are affected by water depth, catch weight, and hauling speed. In addition, the lower part of the gillnet, in contact with the seabed, is subjected to friction. Syversen et al. (2020) have estimated a material loss of 2-4% for the net and a 3-10% for the remaining compartments (Syversen et al., 2020). Therefore, a loss rate of 3% and 6.5% is used in this thesis. Alnes (2022) reported 111 g plastic loss per ton caught for gillnets and a material composition of 93% PA and 7% PP (Alnes, 2022). Data in *Table 8* and *9* has been used to calculate output per FU in *Table 10* and *11.*

Table 9 Data collected on plastic loss from the set gillnet.

Parameters	Value	Unit	References
Loss rate, rope, sinking, and floating elements	6	%	(Syversen et al., 2020)
Loss rate, net	3	%	(Syversen et al., 2020)
Macro plastic loss	111	g/ton catch	(Alnes, 2022)
- Nylon	93	%	(Alnes, 2022)
- Polypropylene	7	%	(Alnes, 2022)

Table 10 Emissions to biosphere per FU for demersal trawl with plastic type, values, and calculation method. FR = fish requirement (3.25 kg), LR = loss rate.

Emissions to biosphere	mg/FU	Formula
Synthetic rubber	572.23	$\frac{Material\ weight}{An. catch\ pr\ vessel^{a} \cdot Lifetime} \cdot FR^{b} \cdot LR^{c}$
Polyethene	39.44	
Nylon	24.75	$Loss\ of\ gear \cdot FR^{b}$
Polypropylene	32.99	
Polyethene	217.21	

[a] Annual catch per vessel.

[b] FR = Fish requirement (3.25 kg), presented in *section 2.2.4 Processing*

[c] Loss rate – loss of fishing gear to the marine environment.

Table 11 Emissions to biosphere per FU for set gillnet with plastic type, values, and calculation method. FR = fish requirement (3.25 kg), LR = loss rate.

Emissions to biosphere	mg/FU	Formula
Polypropylene	45.60	$Plastic\ Input\ fishing\ gear \cdot LR^{a}$
Polyethene	16.59	
Nylon	108.78	
Polyester	4.17	
Nylon	335.50	$Loss\ of\ gear \cdot FR^{b}$
Polypropylene	25.25	

[a] Loss rate – loss of fishing gear to the marine environment.

[b] FR = Fish requirement (3.25 kg), presented in *section 2.2.4 Processing*

2.2.4 Processing

Cod delivered for processing: The DF provides conversion factors for fish requirement (FR) per kilogram final product. For this thesis FU, 3.25-kilogram of cod is required to produce one kilogram of cod files without skin and bones (Fiskeridirektoratet, 2022g).

Processing plant and material use: Data on the processing plant and materials use are collected from Winther et al. (2020) and are based on a salmon slaughtering plant. The plant is 15 000 m^2, processes 90 000 tons of fish annually, and has a 30-year lifetime. Material inputs per ton processed are 6.1 m^3 freshwater input, 0.3 kg of soap, 380 grams of detergent, 0.23 kg of metals, and 0.25 kg of wood per ton of fish processed. There is additional information on waste handling (Winther et al., 2020), but this is out of the scope. The plant is assumed to be a good proxy for processing white fish.

Energy use: Energy used during processing is retrieved from Winther et al. (2020) and is based on a white fish company and the previously mentioned salon slaughtering plant. The electricity demand is 363 kWh per ton processed and 0.13 liter of fuel (Winther et al., 2020).

Packaging: This thesis includes packaging for transportation and sale during processing. Winther et al. (2020) consulted with transportation operators and fish exporting companies to learn about transportation packaging. Cardboard boxes with plastic liners are commonly used to transport frozen fish. Each box can hold up to 25 kg of fish and weighs 2 kg (Winther et al., 2020), and the plastic liners are assumed to be 0.25 kg of polyethylene per unit. Packaging for sale is 50 grams of plastic per kg filet (Loubet et al., 2021).

The presented data for processing are summarized in *Table 12. Table 13* shows the values and calculation methods used to estimate input from the technosphere per FU.

Table 12 Data collected on cod processing, material and energy use, and packaging.

Parameter	Data	Unit	References or assumptions
FR; cod filet without skin and bones	3.25	kg/kg final product	(Fiskeridirektoratet, 2022g)
Salmon slaughtering plant	15 000	m^2	(Winther et al., 2020)
Annual processing	90 000	ton	(Winther et al., 2020)
Lifetime	30	years	(Winther et al., 2020)
Freshwater input	6.1	m^3/ton	(Winther et al., 2020)
Soap	0.3	kg/ton	(Winther et al., 2020)
Detergent	380	g/ton	(Winther et al., 2020)
Metal	0.23	kg/ton	(Winther et al., 2020)
Wood	0.25	kg/ton	(Winther et al., 2020)
Electricity	363	kWh/ton	(Winther et al., 2020)
Diesel	0.13	l fuel/ton	(Winther et al., 2020)
Packaging sale	50	g/kg cod filet	(Loubet et al., 2021)
Transport packaging: cardboard	2	kg/25 kg cod	(Winther et al., 2020)
Transport packaging: plastic	0.25	g/25 kg cod	Assumption

Table 13 Input from technosphere per FU for both cases with Ecoinvent dataset, values, and calculation method. FR = fish requirement (3.25 kg).

Input from technosphere	Value	Formula
building construction, hall, RoW (m^2/FU)	1.81E-05	$\frac{Slaughtering\ plant}{An.catch\ pr\ vessel^{a} \cdot Lifetime} \cdot FR^{b}$
tap water production, conventional treatment, Europe without Switzerland (m^3/FU)	0.02	$Input \cdot FR^{b}$
Soap production, RER (g/FU)	0.98	
Cleaning consumables, without water, in 13.6% solution state, GLO (g/FU)	1.24	
Metal working machine production, unspecified, RER (g/FU)	0.75	
softwood forestry, pine, sustainable forest management, SE (g/FU)	0.81	
electricity production, hydro, reservoir, alpine region, NO (kWh/FU)	1.18	
diesel, burned in building machine, GLO (MJ/FU)	0.015	
polypropylene production, granulate, RER (g/FU)	50	$Input \cdot Final\ Product$
corrugated board box production, RER (g/FU)	80	$\frac{Cardboard\ box/plastic\ liner}{Fish\ pr\ box} \cdot FR^{b}$
packaging film production, low density polyethylene, RER (g/FU)	0.01	

[a] Annual catch per vessel.

[b] FR = Fish requirement (3.25 kg).

2.2.5 Transportation

About half of Norwegian white fish is exported, and the remaining is used in Norway (Klima og miljødepartementet, 2021). The environmental impact of transport and fuel use is not this study's primary focus but is included in a simplified manner with domestic transport from point A to B. The DF statistics of catch distributed by county municipality show that Troms and Finnmark followed by Nordland, had the highest catch value of cod in 2021 for the relevant gear types (Fiskeridirektoratet, 2022d). Bodø is close to the two counties and is selected as point A. Oslo is the municipality with the largest population (SSB, 2022) and is selected as point B. The distance given by Google Maps is used, 1 189 km.

Background data is collected from *Ecoinvent* with the dataset "*transport, freight, lorry with refrigeration machine, 7.5-16 ton, EURO6, R134a refrigerant, freezing, GLO*"*.* The activity represents 1 ton of goods transported 1 km with a controlled freezing system, and it includes the input of fuel, refrigeration machine, and road and vehicle infrastructure. EURO6 is the newest technology level, and R124a is the most used refrigerant (Levova, 2021), as Norwegian trucks are assumed to be modern.

Transportation is included due to the loss of microplastic from tire tread. The *Plastic leak project* reports loss rates and polymer fractions in tire tread for medium/heavy trucks for long- and short hauls. Loss of tire tread per km traveled is 517 mg (long) and 658 mg (short), and polymer fraction is 0.60 (long) and 0.5 (short) (Peano et al., 2020). A long and short haul is not defined. The numbers correspond to Vogelsang et al. (2020), which used an emission factor of 600 mg/vkm and a polymer fraction of 0.55 (Vogelsang et al., 2020). The PLP presents two methods for calculating tire loss for goods transported by trucks. The second method has been used and is based on the mass of goods, distance, total load, tire tread loss rate, and polymer fraction, see *Equation 1* (Peano et al., 2020).

Equation 1

$$TireLoss = \frac{D_{truck_{prod}}[km] \cdot M_{prod}[kg]}{Load_{av}[kg]} \cdot Loss_{truck_{tires}} \left[\frac{kg\ tread}{vhc \cdot km}\right] \cdot ShPolymer_{truck_{tires}}$$

Not all microplastic released from tire wear has the ocean as its final environmental compartment. According to PLP, the final release rate of tire tread to the ocean is 2%, but this number does not include release through runoff in coastal areas due to lacking data (Peano et al., 2020). The final data used in this assessment are presented in *Table 14,* and *Table 15* shows input and output per FU regarding the transportation of the final product.

Table 14 Data collected on transportation of the final product.

Parameters	Value	Unit	References
Distance	1 189	km	(Google Maps, n.d.)
Average load	12 000	kg	(Peano et al., 2020)
Emission factor tires	600	mg/vhc·km	(Vogelsang et al., 2020)
Polymer share	55	%	(Vogelsang et al., 2020)
Final release rate, tire tread, to ocean	2	%	(Peano et al., 2020)

Table 15 Input from technosphere and emissions to biosphere per FU for both cases with Ecoinvent dataset, values, and calculation method.

Input from technosphere	Value	Unit	Formula
transport, freight, lorry with refrigeration machine, 7.5-16 ton, EURO6, R134a refrigerant, freezing, GLO	1.34	tkm/FU	$Weight\ material \cdot Transport\ distance$
Emissions to biosphere	Value	Unit	Formula
tire wear - microplastic	36.95	mg/FU	Equation 1

2.2.6 Production of plastic

Pellets (2-5 mm diameter) are the end product of plastic production and recycling. Activities throughout the value chain are associated with the risk of loss. Both small emissions and major accidents can occur at factories or during transportation. Norwegian pellet loss is estimated to be 0.1 kg/ton of raw material produced, 0.2 kg/ton processed, and 0.1 kg/ton transported (export and import). Norwegian pellet emissions to the ocean are 15.2% of total emissions (Sundt et al., 2020). Data are presented in *Table 16,* and *Table 17* shows output per FU.

Table 16 Data collected on plastic pellet production.

Parameters	Value	Unit	References
Loss rate plastic pellets	0.40	kg/ton produced	(Sundt et al., 2020)
Final release rate to the ocean	15.20	%	(Sundt et al., 2020)

Table 17 Emissions to biosphere per FU for both cases with values and calculation method. LR = loss rate.

Emissions to biosphere	Value	Unit	Formula
Plastic pellets – case with demersal trawl	29.82	mg/FU	$Total\ Plastic\ Input \cdot LR^{a}$
Plastic pellets – case with set gillnet	21.86	mg/FU	

[a] Loss rate – loss of plastic pellets to the environment

2.3 Life cycle impact assessment

The third phase of an LCA is the LCIA. It provides additional information to better understand and evaluate the systems' environmental impacts throughout the life cycle. In this phase, the LCI results are assigned to impact categories representing environmental issues (ISO, 2006).

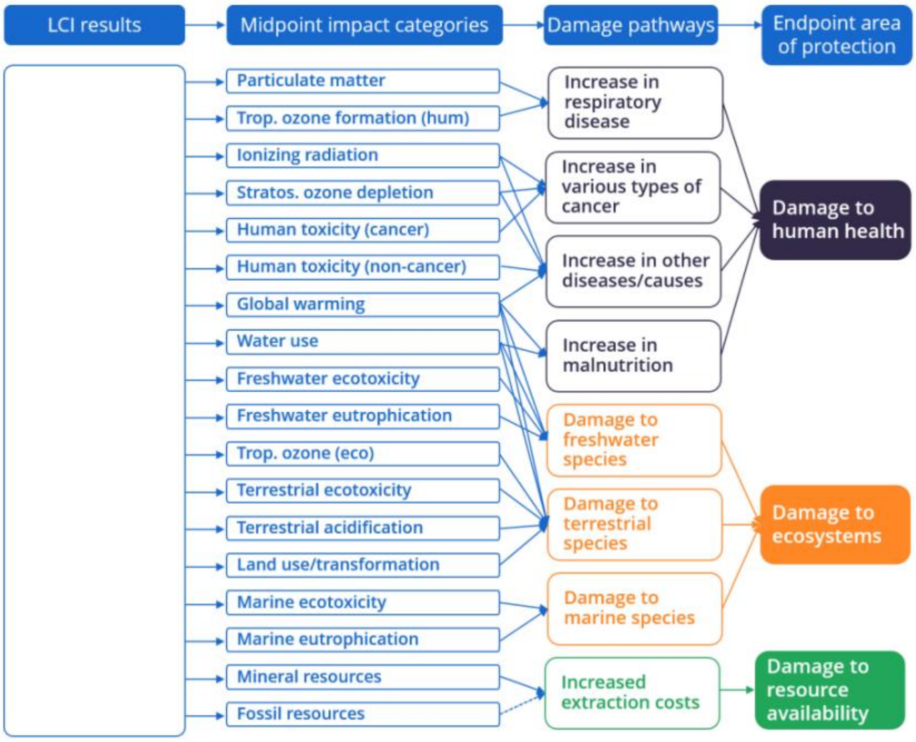


Figure 4 Overview of impact categories and areas of protection covered in the ReCiPe2016 method (European Commision, 2021).

Impact categories can be presented at two levels: midpoint and endpoint, as shown in *Figure 4*. The midpoint method characterizes indicators at a level of cause-effect between resource consumption or emissions. The second level, the endpoint level, aggregates indicators regarding the entities to protect, known as the Areas of Protection (AoPs) (EC-JRC, 2010). ReCiPe2016 is one of the most recent and updated LCIA methods accessible for LCA practitioners (European Commision, 2021). The methodology provides LCIA results and harmonized CF at the midpoint and endpoint level for the global scale (some impact categories can implement CF at a country or continental scale) (Huijbregts et al., 2016). The methodology strives to provide results at both levels in a consistent way. However, it is noted that the two approaches can result in different interpretations (Dong & Ng, 2014). This assessment has used the newest version, ReCiPe2016 v 1.03, midpoint/endpoint (H). ReCiPe2016 defines the AoPs as *Human health* (damage to human health), *Natural Environment* (damage to ecosystem quality), and *Resource scarcity* (damage to resource availability). Seven impact categories at the endpoint level for ecosystem quality (Natural Environment) in species.yr are used in this thesis, in addition to two newly developed categories. The categories from ReCiPe2016 are climate change for terrestrial and freshwater ecosystems, ecotoxicity for terrestrial, freshwater, and marine, eutrophication for freshwater and marine, and acidification for terrestrial.

The CF on macroplastic debris entanglement in the marine environment is the continued work of the published preliminary Species Sensitivity Distribution (SSD) by Høiberg et al. (2022). The SSD is field based and includes data on 20 marine mammals, birds, and turtles from different regions and populations. The SSD is developed using data on species-specific sensitivities to entanglement, concentrations of plastic debris with spatial variations, and potential exposure areas. The paper applies a threshold of 5% annual entanglement rate of populations and defines species affected by macro plastic as chronic entanglement and mortality (Høiberg et al., 2022). The SSD model has been translated into an effect factor (EF) and combined with a fate model. The CF for entanglement in this assessment has a regionalized impact pathway for Norway. The release point is Tromsø, and the runtime is one year (Høiberg et al. in prep).

A simplified fate and CF have been published for tire wear microplastic loss. The authors have developed the fate factor, and it is based on sedimentation, degradation, and fragmentation rates from literature and expert estimations (Corella Puertas et al., 2022). The CF is based on the existing exposure and EF for microplastic in aquatic environments by Lavoie et al. (2021). The CF is published at the midpoint and endpoint levels for best, worst, and average cases (Corella Puertas et al., 2022).

The preliminary CF for macroplastic debris entanglement and the CF for road wear particles have been converted from their original impact assessment matric to species.yr. The CF for entanglement is 7.21E-19 species.yr/kg plastic and for tire wear 7.94E-12 species.yr/kg plastic. Calculations are shown in A*ppendix 2.*

2.4 Software

Brightway 2 is a Python-based open-source framework developed and used by researchers and academics. It is divided into several packages, the umbrella package containing documentation and three additional main packages for storing and searching databases and LCIA methods, calculating LCA results, and analyzing input data, methods, and results (Brightway, 2013).

Activity Browser (AB) is an open-source software for conducting advanced LCAs and builds on the framework of Brightway 2. The software and its graphical user interface make general tasks more straightforward and intuitive, such as managing databases and projects, modeling inventories and scenarios, calculating LCA results, and analyzing results. Furthermore, the use of AB can significantly speed up tasks that can be standardized compared to the use of Brightway 2 (Steubing et al., 2020). For these reasons, has the AB been utilized. For results, a cut-off level of 6.3% is used, the recommended value by the AB. Processes contributing less is categorized as "Rest". Changing this to a lower value would give more detailed information, but for this thesis, only the top contributing processes were essential to show.

Excel has been used to calculate the environmental impact of macroplastic entanglement and loss of microplastic from tire wear. This can be seen in A*ppendix 6* (the Excel file named *Inventory data and calculations*).

3 Results

The following section presents the inventory and LCIA results.

3.1 Inventory result

Inventory results in this section identify plastic flows within the two cases and are based on the entire life cycle inventory per functional unit, A*ppendix 3* and *4*.

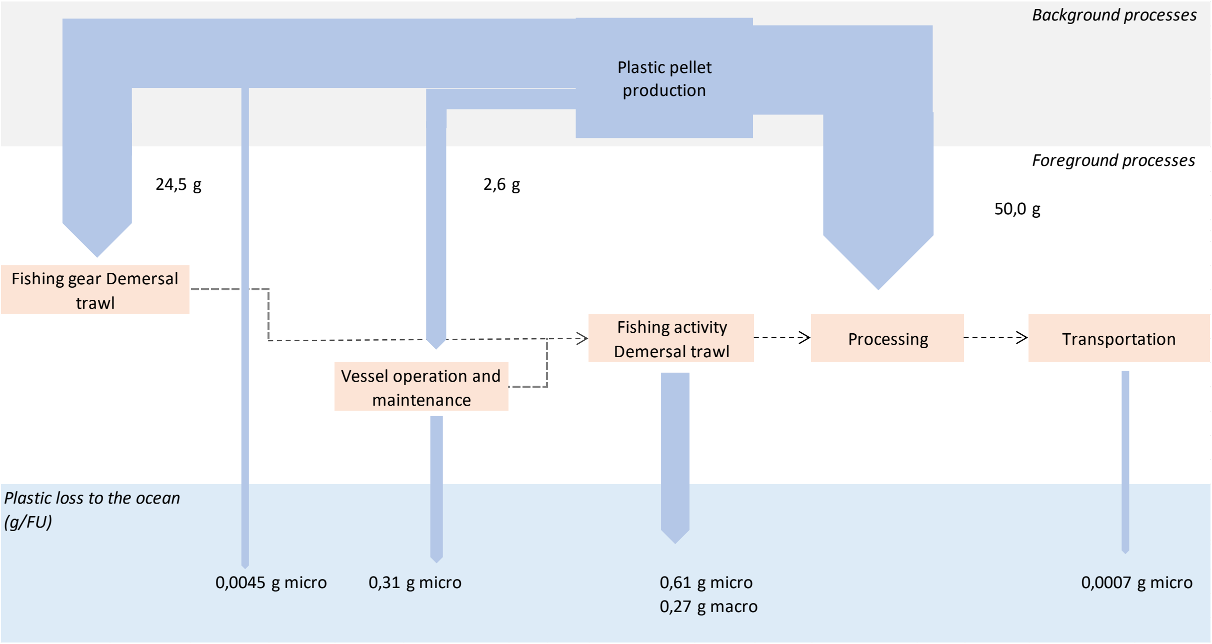


Figure 5 Illustration of plastic flows for the included life cycle stages for demersal trawl, given in the unit grams per FU.

Figure 5 illustrates the plastic flows gathered per FU for the included life cycle stages for the demersal trawl. The highest plastic requirement is caused by processing with 50.01 g per FU, followed by fishing gear with 24.54 g per FU. The most significant loss to the ocean is caused during fishing activity due to the loss of fishing gear at 0.88 g per FU, followed by the loss of microplastic during maintenance with 0.31 g per FU.

Figure 6 illustrates the plastic flows for set gillnet. The plastic requirement for processing is the same for the case with demersal trawl, but the requirement for fishing gear is 4.65 g per FU, 81% lower than the plastic requirement for demersal trawl per FU. Plastic loss to the ocean is lower for the case with gillnet. Fishing activity with set gillnet has the most significant plastic loss at 0.54 g per FU, followed by maintenance at 0.26 g per FU.

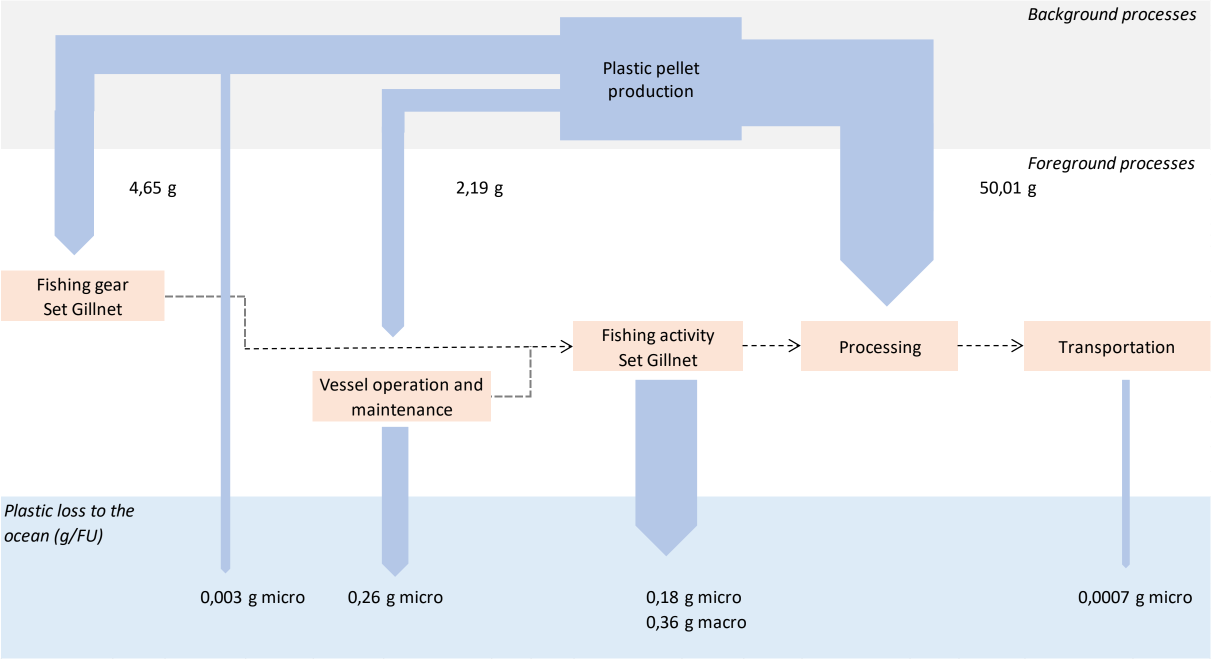


Figure 6 Illustration of plastic flows for the included life cycle stages for set gillnet, given in the unit grams per FU.

3.2 Life cycle impact assessment results – Midpoint

The life cycle impact assessment results for the midpoint level, and endpoint in the following section, are produced from the elementary flow contributions retrieved from the Activity Browser, *Appendix 7* (the Excel file named *Results from AB*).

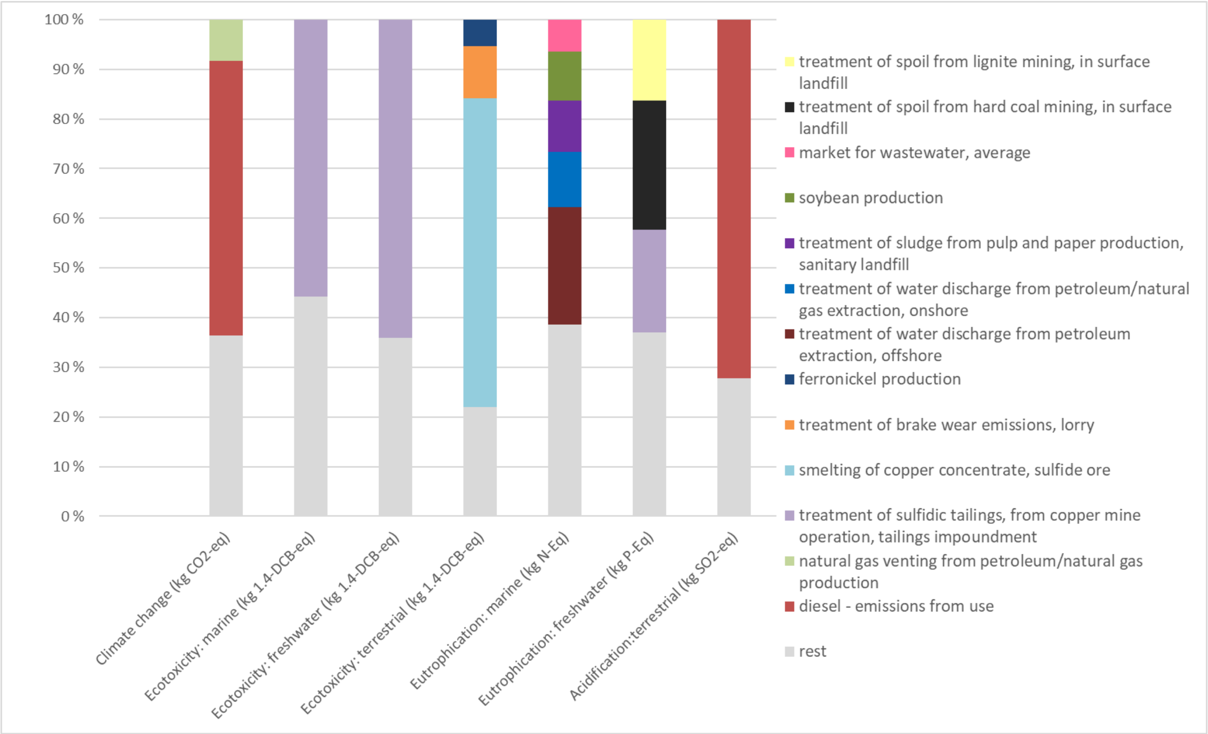


Figure 7 Impact assessment at the midpoint level for demersal trawl (relative share).

Figure 7 presents the elementary flow contribution at the midpoint for the demersal trawl in relative share for seven impact categories. The overview shows the processes contributing to more than the cut-off level (6.3%) of the assessment's total impacts. Processes contributing to less are categorized as *rest*. Emissions from diesel usage contribute to about 55% of potential global warming and 72% to potential acidification. Treatment of sulfidic tailings from copper mine operations contributes to about 56% of ecotoxicity for marine ecosystems and 64% for freshwater ecosystems. Smelting of copper concentrate, sulfide ore, contributes to 62% of potential ecotoxicity for terrestrial ecosystems.

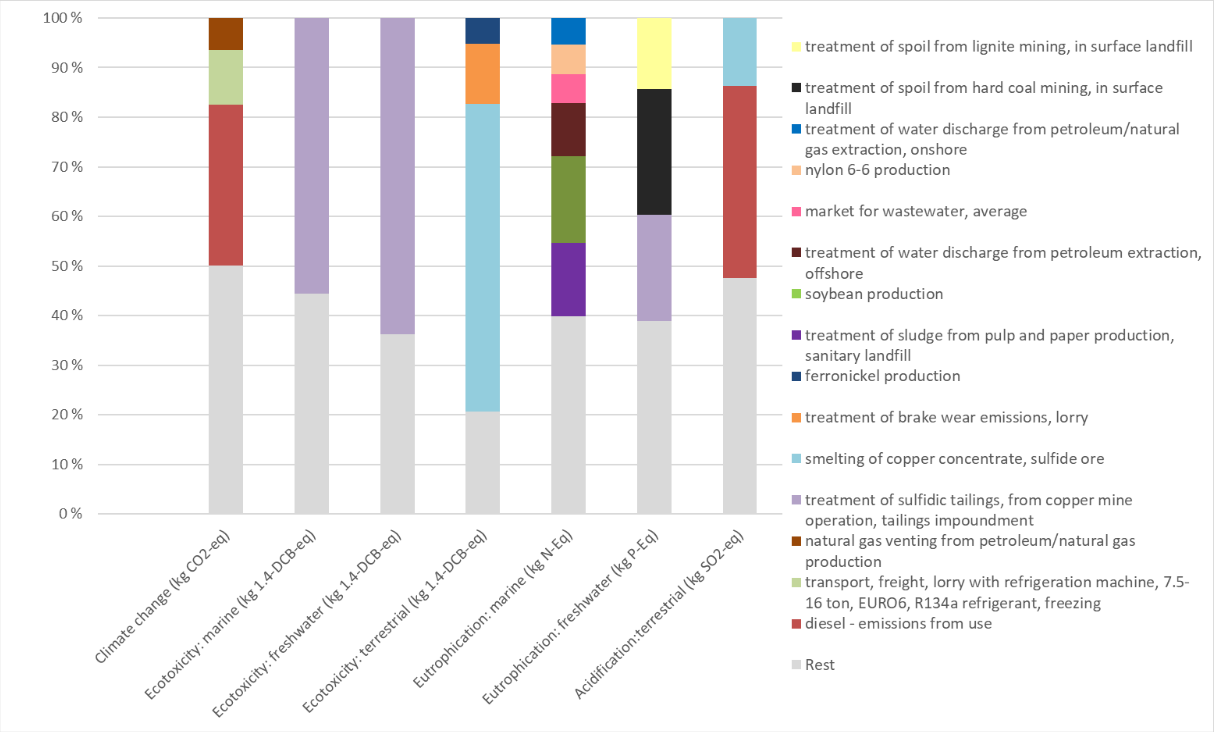


Figure 8 Impact assessment at the midpoint level for set gillnet (relative share).

Figure 8 presents the elementary flow contribution at the midpoint for the set gillnet in relative share for the same seven impact categories. Emissions from diesel usage contribute to about 32% of potential global warming and 38% to potential acidification. Treatment of sulfidic tailings from copper mine operations contributes to about 55% of ecotoxicity for marine ecosystems and 64% for freshwater ecosystems. Smelting of copper concentrate, sulfide ore, contributes to 62% of potential ecotoxicity for terrestrial ecosystems. These mentioned processes have the most significant contribution. In general, are more processes above the cut-off-level for the case with gillnet.

Table 18 presents the absolute share to compare the cases, indicating that trawl has a higher environmental impact across all categories.

Table 18 Impact assessment at the midpoint level for trawl and gillnet (absolute share).

Impact category (ReCiPe2016 v1.03, midpoint (H))	Trawl	Gillnet	Unit/FU
Global warming potential (GWP1000)	5.49E+00	2.41E+00	kg CO_2-eq
Marine ecotoxicity potential (METP)	4.63E-01	3.88E-01	kg 1.4-DCB-eq
Freshwater ecotoxicity potential (FETP)	3.52E-01	2.98E-01	kg 1.14-DCB-eq
Terrestrial ecotoxicity potential (TETP)	3.67E+01	3.08E+01	kg 1.14-DCB-eq
Marine eutrophication potential (MEP)	2.72E-04	1.92E-04	kg N-eq
Freshwater eutrophication potential (FEP)	7.42E-04	6.02E-04	kg P-eq
Terrestrial acidification potential (TAP)	3.34E-02	1.07E-02	kg SO_2-eq

3.3 Life cycle impact assessment results - Endpoint

The LCIA results at the endpoint level present eight impact categories from ReCiPe2016 assessing ecosystem quality in species.yr and the newly developed CF for macroplastic entanglement and microplastic tire wear in marine ecosystems.

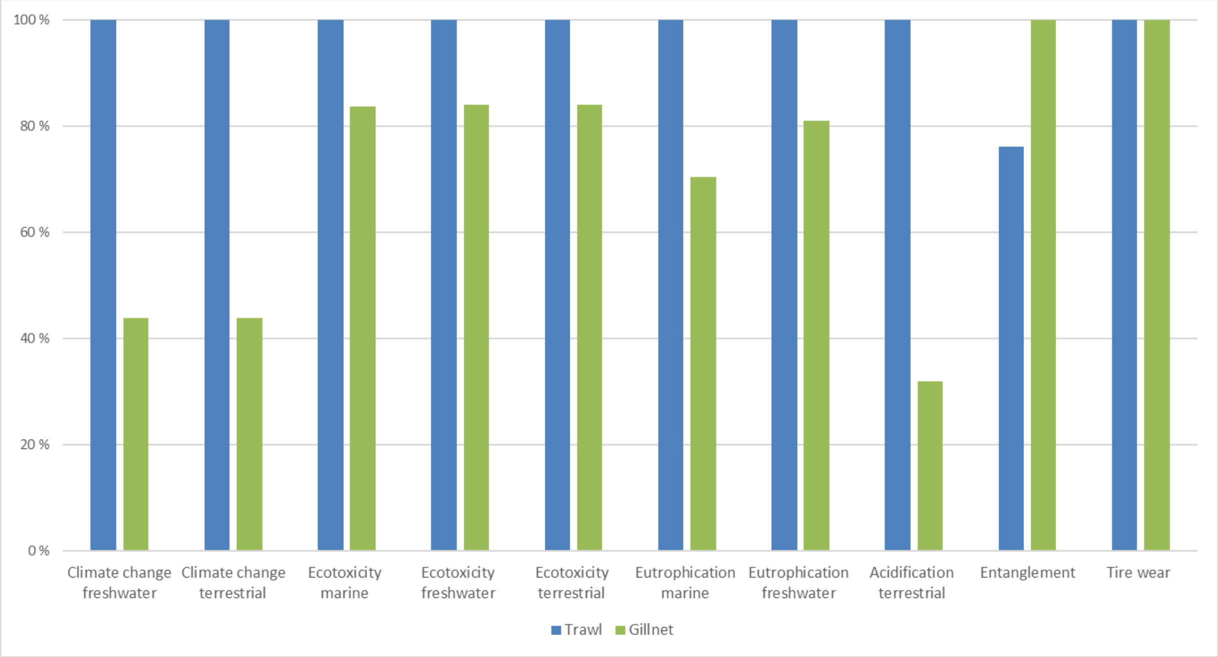
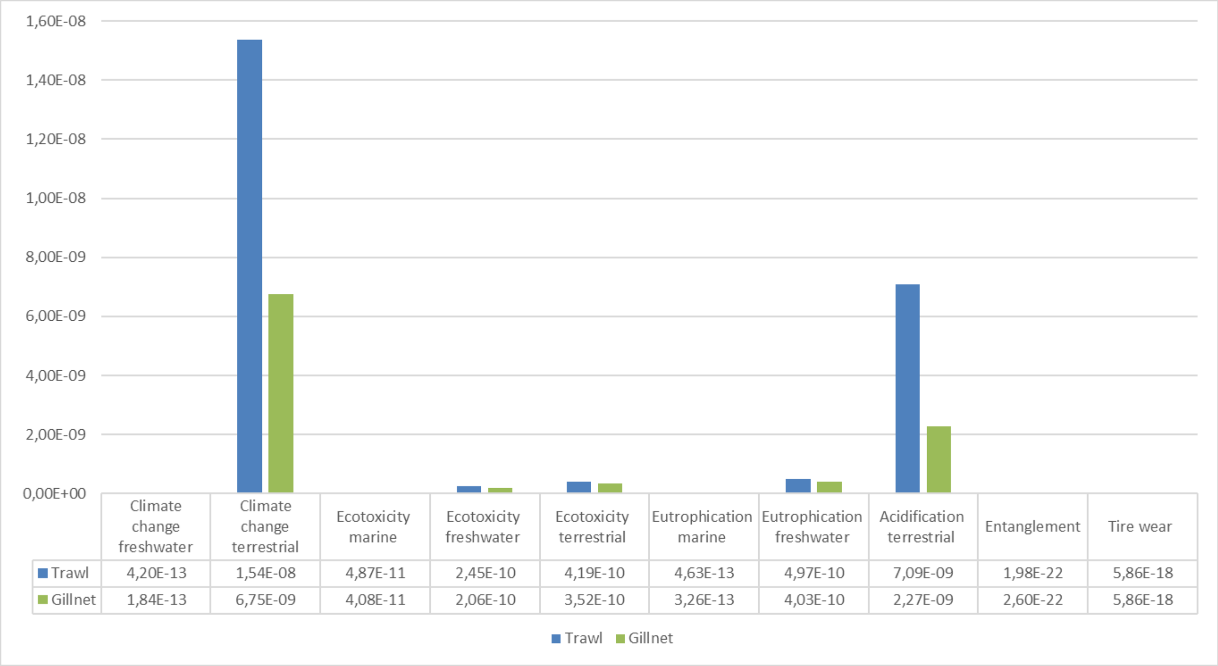


Figure 9 Impact assessment at the endpoint level in relative share, comparing potential impacts of all life cycle stages for the trawl and gillnet cases.

Figure 9 compares the potential impacts of all life cycle stages for the case with trawl to the case with gillnet in relative share. The figure shows that trawl as a higher potential impact in all categories except two. Gillnet has the highest potential impact for entanglement, and impacts cause by tire wear emissions are equal in both cases.



	Climate change freshwater	Climate change terrestrial	Ecotoxicity marine	Ecotoxicity freshwater	Ecotoxicity terrestrial	Eutrophication marine	Eutrophication freshwater	Acidification terrestrial	Entanglement	Tire wear
■ Trawl	4,20E-13	1,54E-08	4,87E-11	2,45E-10	4,19E-10	4,63E-13	4,97E-10	7,09E-09	1,98E-22	5,86E-18
■ Gillnet	1,84E-13	6,75E-09	4,08E-11	2,06E-10	3,52E-10	3,26E-13	4,03E-10	2,27E-09	2,60E-22	5,86E-18

Figure 10 Impact assessment at the endpoint level in species.yr, comparing potential impacts of all life cycle stages for the trawl and gillnet cases.

Figure 10 illustrates the two cases' potential impacts in species.yr. The highest potential loss is observed in the climate change: terrestrial ecosystems category, with 1.54E-08 species.yr for trawl and 6.75E-09 species.yr for gillnet. Acidification: terrestrial is the second-highest impact category, with 7.09E-09 species.yr for trawl and 2.27E-09 species.yr for gillnet. The impact of plastic is associated with the lowest potential loss. Entanglement shows the lowest potential loss, with 1.98E-22 species.yr for trawl and 2.60E-22 species.yr for gillnet. The potential loss due to tire wear emissions to the ocean is 5.86E-18 species.yr.

4 Discussion

This section provides an interpretation and discussion of various aspects, including the system boundary, results, methodological choices, and areas for further research. Data are derived from reliable estimates and sources, aiming to accurately represent the life cycle of the cod catchment by Norwegian fisheries using the two gear types. However, one of the overarching challenges when performing LCAs is acquiring sufficient, precise, and representative data (Ziegler et al., 2016), and this is also the case in this LCA. The thesis entails high data uncertainty due to limited available literature and knowledge gaps concerning the topics addressed and will be further discussed in the sections below. Despite this, data is considered transparent and robust enough to evaluate the new characterization factors' impact on the marine environment and to compare cases.

4.1 System boundary

The system boundary describes the key elements of the physical system according to the assessment’s goal and scope definition. Simultaneously, it is one of the main limitations of the LCI phase (ISO, 2006) and is therefore discussed before interpreting results.

The scope of this thesis is limited to the catchment of wild cod with demersal trawl or set gillnet by Norwegian commercial fisheries in the Norwegian fishing zone, and as a result, the scope fails to capture the entire Norwegian seafood industry. To obtain a complete quantification of plastic loss from fish-related activities in Norwegian seawater, the scope would need to include aquaculture, recreational fishing, the foreign fleet in Norwegian waters, and all species and fishing equipment used by Norwegian fisheries. These choices potentially affect the result, for example, fishing gear and catch species. Syversen et al. (2020) quantified plastic loss from 14 gear types, and their result revealed a wide variation in plastic loss, ranging from 0.3 tons to 102 tons annually between individual gear types. Furthermore, the study by Alnes (2022) quantified the extent of plastic loss from six gear types and its correlation with the annual catch. The study determined that trawl gear had a plastic loss of 0.08 kg per ton catch and gillnet gear 0.11 kg. However, despite having a lower plastic loss per ton catch, trawl gear accounted for a significantly higher overall annual loss of 130 tons, compared to gillnet gear, primarily due to its higher annual catch (Alnes, 2022). These literature findings underscore the importance of acknowledging the scope when interpreting this thesis's results per FU.

ISO14040 gives an example of several life cycle stages, unit processes, and flows that should be considered when setting the system boundary, including the use and disposal of products (ISO, 2006). However, as illustrated in *Figure 1*, the system boundary in this assessment does not include *Consumption* and *End-of-life treatment* or wholesaler/retailer. The inclusion of wholesaler/retailer and consumption as steps along the supply chain could be essential due to the potential loss of edible products. Product loss late in the supply chain, in this case after processing, has a higher impact than the early loss of non-processed products as more must be replaced. However, these two processes are equivalent in both cases and would not impact the comparison. In addition, there is limited data on such loss rates, which also emerges from Winther et al. (2020), who left product losses along the supply chain out of scope.

Waste treatment of materials has environmental impacts connected to them, but with this LCA's focus on plastic loss to the marine environment and comparing the two cases, it is not included in the system boundary. Biowaste, non-sorted waste, and packaging from transportation and sales will need end-of-life treatment. However, amounts are the same in both cases and would not affect the comparison. Fishing gear and vessel(parts) delivered for waste treatment could influence the comparison but have not been included due to limited data. In this assessment, plastic loss from end-of-life treatment is considered not to be significant and therefore not included following *What a Waste 2.0's* classification of Oslo's waste collection rate to be 100% (Kaza et al., 2018) and the *PLP* classifying in-home non-flushable products, e.g., plastic packaging, to have a littering rate of 0% (Peano et al., 2020). However, Sundt et al. (2020) state that waste management contributes to 5.1% of Norwegian microplastic emissions. Of this, 88.6% is connected to biological waste from wrong source sorting and the collection in plastic bags (Sundt et al., 2020). It could be the case with biological waste in this thesis, but it was omitted.

Other limitations linked to the goal and scope definition are assumptions on other potential sources of plastic loss. First, zero plastic loss was assumed beyond fishing gear from the fishing activity, although additional loss is reported in literature. For instance, *A deep dive into our plastic ocean* reports 10 tons of beach litter in Norway in the last 1-3 years, of which the total weight was 7.5% buoys and floating elements and 4.5% fishing creates (Mepex et al., 2020). However, information is limited and therefore not included. Another assumption is related to the mat that protects the trawl from seabed damage, which has a high material loss. This assessment assumes that 100% of fishers use this mat, but alternatives are starting to be used to reduce plastic loss. Syversen et al. (2020) assumed the same due to insufficient data on the new alternatives. Finally, this study does not include by-product utilization, further explained in *section 4.3 Interpretation of LCIA results - Midpoint*.

4.2 Interpretation of inventory results

The inventory result per FU can be used to understand and illustrate plastic flows within the system. *Figures 5* and *6* help identify hot spots for plastic loss from the technosphere to the biosphere (the marine environment) within the system's life cycle. The figures illustrate that the greatest plastic loss per FU is related to the *fishing activity,* followed by *vessel operation and maintenance,* for both cases. This indicates that these two processes have the greatest potential for reducing the environmental threat of plastic accumulation in the ocean if measures were to be successfully introduced. *Table* 19 summarizes the data visualized in *Figures 5* and *6*.

Table 19 Summary of data from Figure 5 and 6 – plastic flows for the two cases in g/FU

	Demersal Trawl	Set Gillnet
Plastic input	77.17	56.84
Plastic lost to the marine environment	1.21	0.80
Plastic lost from the fishing activity	0.89	0.54
Loss of microplastic from the fishing activity	0.61	0.18
Loss of macro plastic from the fishing activity	0.27	0.36
Plastic loss to ocean/plastic input for the FU	1.56%	1.41%

Table 19 shows that cod fished with demersal trawl require 22.33 g of plastic per FU more than cod fished with set gillnet. The trawl's plastic loss to the environment is also greater, with 0.41 g more lost per FU, and it has the most significant loss of microplastic from fishing activity. However, the gillnet has a higher loss of macroplastic. This finding is not unique and is supported by literature. Clean Nordic Oceans have assessed the risk of losing fishing gear, ghost fishing after loss, and the risk of lost gear contributing to additional loss of new gear. In their assessment, gillnet is the equipment with the highest risk in all three areas (Langedal et al., 2020). The risk of losing passive gear (e.g., gillnets) is significantly greater than losing active gear (e.g., trawls) as they are more exposed to the power of nature (weather and ocean currents), can easily get stuck on the seabed, rip during hauling, or collide with other vessels and gear types (Nordic Council of Ministers, 2020).

The presented numbers for plastic loss can seem minor. However, it is essential to note that the loss represents the catchment of 3.25 kg of cod and is affected by the system boundary, limitations, and data uncertainty. However, if total plastic loss per FU were scaled to represent the total Norwegian catch of cod with trawl (120 423 tons) or with gillnet (85 352 tons) in 2021, these values would suddenly become more significant. Plastic loss from trawling is then estimated to be about 348.32 tons annually, and 246.67 tons annually from gillnet fishing.

As a part of the interpretation of plastic loss per FU to the environment, the result of this assessment is compared to literature. Loubet et al. (2021) have quantified micro and macroplastic loss from the French seafood supply chain with the FU: consumption of 1 kg fish, using a conversion factor of 2.23 kg per kg final product. The assessment includes abandoned, lost, or otherwise discarded fishing gear, loss of marine coatings, plastic pellets, tire abrasion, and mismanaged plastic during end-of-life treatment. Cod caught with bottom trawl has, in their assessment, a total plastic loss of 0.48 g per FU and a loss from the fishing activity of 0.36 g per FU (macro plastic) (Loubet et al., 2021). Beyond this source, literature on plastic loss from fisheries presents numbers from the fishing activity, not the entire life cycle. For this reason, only fishing gear loss is compared in *Table 20*.

Table 20 Plastic loss from fishing activity compared to literature. To compare the numbers on a shared basis, they are scaled to represent g of plastic loss per 3.25 kg of fish.

Reference	Trawl	Gillnet	Comment
This assessment	0.89	0.54	
micro	0.61	0.18	Loss-rates by Syversen et al. (2020)
macro	0.27	0.36	Loss-rates by Alnes (2022)
Syversen et al. (2020)	0.48 (0.26 – 0.68)	0.32 (0.20 – 0.51)	All types of species, Norway
Alnes (2022)	0.27	0.36	All types of species, Norway
Loubet et al. (2021)	0.52		Cod, bottom trawl, France. Macro plastic
Hellesund (2022)		0.33	Cod caught in Norway. Macro plastic loss.

Table 20 shows that plastic loss from fishing gear in this assessment is higher than literature but in the same order of magnitude. A reason for it being greater could be the decision to base plastic loss on two sources, potentially causing double counting. However, this was concluded as a reasonable assumption as Syversen et al. (2020) do not include all losses and that most loss in their report is microplastics, even though some larger fractions occur. The maximum size they report is not specified. Loubet et al. (2021) and Hellesund (2022) present loss rates for macroplastic loss, but only for one gear type each. Alnes (2022) presents a loss rate for both gear types but does not specify material size. However, as the report is based on data from the literature, sales numbers, waste companies, and collected equipment, it was decided as reasonable to assume the numbers represent macroplastic loss.

Knowledge on the causes of wear and tear of fishing equipment is known. However, there is limited information and quantifications on the material loss caused by the specific causes of different gear types as they are difficult to distinguish from one another (Syversen et al., 2020). It can also be challenging to determine the origin of plastic and the year it was lost when collected from the ocean or beaches (Deshpande et al., 2020). Additionally, not all plastic in the marine environment is available for ocean or beach cleanups. An assessment of macro litter in the south-eastern North Sea found the litter density to be about 40 times greater at the seabed than at the ocean surface. Of the seabed litter, about 76% of the items were fishing-related and made out of plastic (Gutow et al., 2018). Depending on how plastic loss numbers are estimated, the inclusion or not of seabed plastics can significantly impact reported loss rates. A literature review of 68 publications reviewing annual loss rates of fishing gear loss found rates varying from 0 – 79.8% for nets (Richardson et al., 2019).

Syversen et al. (2020) addressed data limitation in their study by presenting findings with inherent uncertainties and noting that the presented figures in their paper come with high uncertainty. They compared data from multiple sources and exercised caution in their numerical analysis. The uncertainties in their report are linked to variables such as the amount of fishing equipment per vessel, the loss rate for different gear types or parts, and measurements or tests conducted. Despite the significant uncertainty, they consider their results reasonable. With Syversen et al. (2020) as a data source for fishing gear and fishing gear loss, their uncertainty reflects this thesis uncertainty regarding this topic.

4.3 Interpretation of LCIA results – midpoint

Figures 7 and *8* provide valuable insights into which processes contribute to the impact categories at the midpoint level exceeding the 6.3% cut-off-level described in *section 2.4 Software*. For marine and freshwater ecotoxicity, treatment of sulfidic tailings from copper mine operations was the only contributor above the cut-off level, while for *climate change* processes related to fuels were the primary contributors. For the additional impact categories, multiple processes were found to contribute. These findings provide valuable insights and knowledge to fisheries and policymakers, enabling them to develop mitigation strategies and reduce environmental impacts.

Table 18 presents LCIA results at the midpoint level in absolute values for both cases. The results shows that cod caught with the demersal trawl exhibits higher potential impacts across all impact categories, compared to set gillnet. Making set gillnet the preferred catchment method when addressing environmental impacts. However, it is important to note that values should be used on a comparative basis and not interpreted as absolute due to the inherent principles of LCA and the impact assessment methods, and assumptions and data uncertainties effect on values.

With these limitations in mind, this section proceeds to discuss and compare the LCIA results for the established impact category for *climate change* with findings from literature. This analysis enables a comprehensive understanding of the context, key findings, potential research gaps and areas for improvement. *Table 21* presents the comparison.

Table 21 Comparison of GWP at the midpoint level between this assessment and literature

Reference	Trawl	Gillnet	Comment
	kg CO_2-eq		
This thesis	5.49	2.41	FU: kg edible product delivered to wholesaler Conversion factor: 3.25.
(Winther et al., 2020)	1.6 – 2.5		FU: kg edible product delivered to wholesaler Conversion factor: 1.5 to 3.65 Whitefish industry 60% by-products utilization.
(Winther et al., 2009)	2.20-3.78		FU: kg edible product delivered to wholesaler Round cod: 1.55 – 2.44 By-products are used for feed (39%).
(Svanes et al., 2011)	Loins: 4.4		Autoline fisheries - Sweden Fu: 1 kg final product delivered to retailer
(Guttormsdóttir, 2009)	5.14		FU: 1 kg of frozen light salted cod filets caught in the Icelandic sea by trawl. Use a yield of 50%
(Ziegler et al., 2003)	3.782	0.912	Swedish cod fishery in the Baltic Economic allocation FU: consumer package of frozen cod fillets (400g) – representing 75% of the product value

Table 21 shows that CO_2-eq per FU in this thesis are higher than in the newest literature and more comparable to 10-15-year-old literature. One explanation for this can be this thesis's choice of leaving by-product utilization out of the scope. The assessment of seafood products by Winther et al. (2020) used a by-product utilization percentage of 60% for the white fish industry at processing, and 90% in the market, allocated by mass. As a result, inputs and impacts up to the point of by-product production have been allocated in their assessment, lowering the main product's impacts. The impact of by-product utilization was tested for fresh haddock as a part of their assessment. When going from zero by-product

utilization to an average utilization, 61.5% of GHG emissions were reduced. Svanes et al. (2011a) have looked into the same. The GWP of loins was reduced by 10.1% when utilizing the whole fish instead of discarding guts and heads. The two examples show the importance of utilizing the entire fish product and the importance of a circular fishing industry. However, it is not included in this thesis. The main goal has been to test the impacts of the newly developed CF on plastic loss to the marine environment. Allocating for by-product utilization in this thesis would reduce all impacts, also the impacts caused by plastic loss. With the ratio between categories staying the same, it was decided to keep by-product utilization out of the assessment scope.

To gain further knowledge regarding the differences with literature, the processes contributing to the foreground system for climate change (GWP) are illustrated with a Sankey diagram created in AB, *Figure 11.* The diagram for demersal trawl shows that 71.0% of GWP is caused by diesel burned during fishing activity, diesel production, and the petroleum market – making it interesting to look further into diesel. Fuel consumption per FU is closely related to the fish requirement per FU (3.25 kg cod). When looking into the literature, the conversion factors vary. For instance, Winther et al. (2020) used a fish requirement of 1.5 - 3.65, and Winther et al. (2009) 1.55 - 2.44 kg. Reducing this assessment's fish requirement from 3.25 kg to 1.5 kg for fuel during fishing would reduce total emissions by 39.4% for the trawl. The assessment's fish requirement and lack of by-product use could explain higher emissions than in the literature.

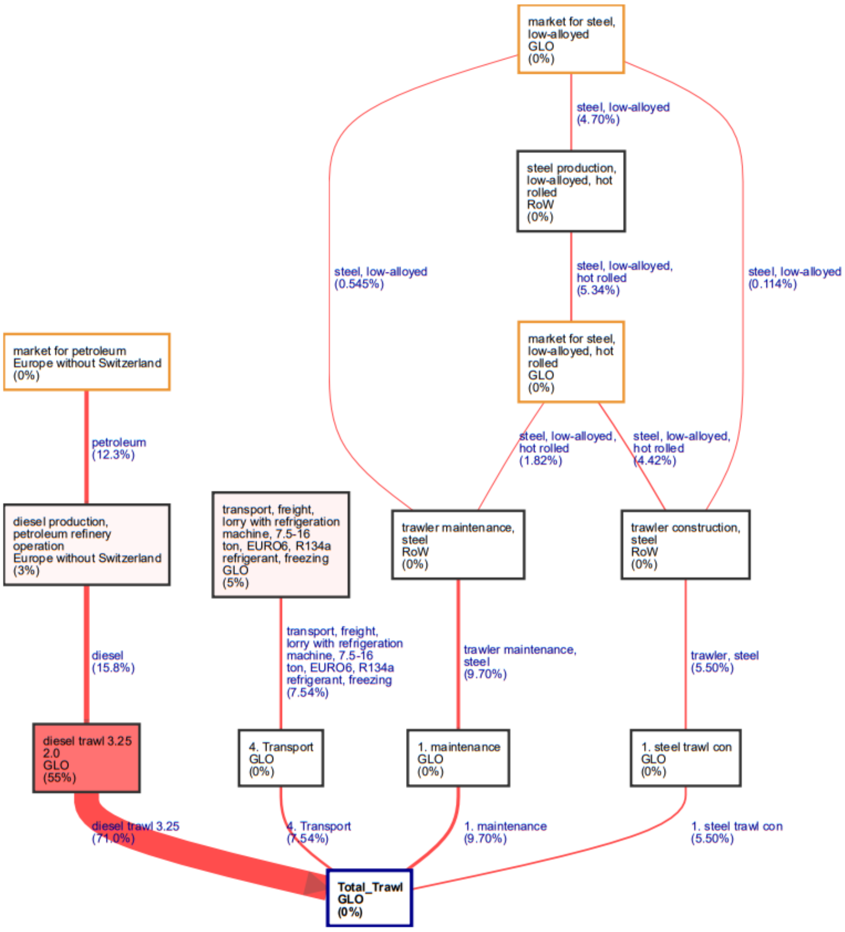


Figure 11 Sanky diagram from AB for climate change - GWP in the case of the trawl.

4.4 Interpretation of LCIA results – endpoint

The LCIA results at the endpoint level are presented for ecosystem quality in species.yr, local species loss integrated over time (Huijbregts et al., 2016). *Figure 9* indicates that fishing cod with demersal trawl leads to a higher potential loss of species in seven out of the nine impact categories considered in this thesis. Set gillnet demonstrates the highest potential loss for entanglement due to a greater loss of macroplastic. Furthermore, tire wear exhibits an equal impact in both cases due to the same transportation distance and vehicle. These findings indicate gillnet as the preferred catchment method when assessing ecosystem quality but simultaneously highlight the need to evaluate potential trade-offs carefully.

Looking further into the results presented at the endpoint level, *Figure 10* clearly illustrates that the highest impact in species.yr for both cases are within the impact category *climate change, terrestrial ecosystems*, followed by *acidification, terrestrial.* Sanky diagrams for both cases tell more about processes in the foreground system responsible for the potential loss, shown in *Appendix 5*. Diagrams for *climate change, terrestrial ecosystems* show that diesel used during fishing accounts for the most significant fraction, 71.0% for trawl and 41.6% for gillnet, followed by maintenance, transportation, and construction in both cases. Diagrams for *acidification, terrestrial,* show that diesel used during fishing accounts for the highest share, 79.4% for trawl and 44.5 for gillnet, followed by maintenance. This finding indicates that marine diesel and maintenance have the highest potential for improvements regarding ecosystem quality.

Interestingly, the most significant impacts on ecosystem quality are terrestrial. The assessed system is a marine industry where fishing occurs offshore, and onshore activities such as processing are located in coastal regions. However, this result can be explained by the situation described in the introduction, that LCA was initially developed to assess land-based products, focusing on impacts on terrestrial and freshwater ecosystems, and lack impact categories focusing on marine ecosystems and drivers of marine biodiversity loss (Woods et al., 2016). As illustrated in *Figure 4,* the pathway *Damage to marine species* is only covered by two midpoint impact categories: *Marine ecotoxicity* and *Marine eutrophication*. ReCiPe2016 does not have impact categories assessing *Climate change* or *Acidification* for marine ecosystems. The fact that ReCiPe has few marine impact categories makes it difficult to assess the extent of the CF for marine plastic compared to other marine categories. As few categories assess impacts on the marine environment, there are few inventory links to the marine ecosystem in databases, and little is characterized to the ocean. With further development of characterization factors, these links will likely be developed.

This assessment has aimed to assess species loss integrated over time from the newly developed CFs and the established categories in ReCiPe. The thesis LCIA results show that macroplastic entanglement from demersal trawls caused the potential impact of 1.98E-22 species.yr and set gillnet 2.60E-22 species.yr. Microplastic loss from tire abbreviation is equal for both cases with 5.86E-18 species.yr. Compared to the established impact categories, potential impacts from tire wear and entanglement are significantly smaller. Compared to climate change, terrestrial ecosystems potential impacts are smaller with a factor of around 10^10 and 10^14, but only with factors from about 10^7 and up to 10^11 compared to the marine impact categories. However, when interpreting these results, it is important to note that the CF methods were, as mentioned in *Section 2.3*, developed in another impact assessment matric and later converted to species.yr, potentially influencing the results.

The impact of plastic loss can seem minor compared to the other impact categories. However, they are essential for assessing a holistic system. The LCI includes loss of micro and macroplastics where data have been available. But as mentioned in the discussion of the system boundary, some plastic losses still have not been included due to knowledge gaps in the literature. In addition, not all impacts of this thesis's plastic-loss inventory have been assessed. Of total plastic loss to the marine environment in weight, 79% is not assessed for trawl, and 57% for gillnet, as no CF has been developed to assess the impacts of microplastic loss from marine coatings, fishing gears, and plastic pellets. An exposure and EF for quantifying aquatic micro- and nano-plastics have been developed. However, a proper fate model is needed to quantify the impacts and generate the lacking CFs (Lavoie et al., 2021). In addition, the environmental impacts of ingesting macroplastic have not been assessed.

The CF used to assess plastic impacts in this thesis is still preliminary and will be further developed. In the published papers, the authors point out some important factors which can impact the result. For instance, the developed SSD does not differentiate between plastic items' size and shape (Høiberg et al., 2022). The associated risk for entanglement is more likely with some plastic debris than others. For example, fishing gear, plastic bags, and balloons are ranked high for entanglement (Wilcox et al., 2016). With an effect factor for lost fishing gear, instead of macroplastic in general, the impact would likely be more significant. Further, the published SSD for marine plastic debris entanglement is linked to uncertainty concerning underlying data, modeling steps, and assumptions. The SSD is field-based, and its input data is limited but diverse. The model aims to include a broader range of taxa and differentiate in regional biodiversity, plastic debris size, animal shape, and body size (Høiberg et al., 2022). In addition to the CF for tire wear, Corella Puertas et al. (2022) developed a CF for expanded polyester. The same exposure and EF are used for both CF and the authors developed new fate models for the two cases. The results/CFs turned out different and revealed the importance and need for CF considering different polymers. Further, the CF for tire wear microplastic emissions has high uncertainties and encourages further work. Some of the uncertainties are related to polystyrene's degradation behavior in aquatic environments, plastic fragmentation, and sedimentation rates. Results in the paper are presented with uncertainty bars, with a best and worst-case scenario (Corella Puertas et al., 2022).

While uncertainties surrounding plastic loss and its potential impacts on the marine environment would have been intriguing to test, such an analysis has not been conducted. This is primarily since a change in plastic loss would only lead to a linear change in LCIA results for the new CFs. An uncertainty analysis with linear change may not provide significant insights, add value, or provide new or unexpected information. Uncertainty analyses are typically useful when the outcome of the test has a complex dependence and can identify sources of uncertainty that may substantially impact the result or provide a new understanding of the system. With how the CF for entanglement and tire wear has been developed, it is only affected by plastic loss in weight. Sensitivity analysis regarding plastic impacts could be more interesting with a more detailed CF, which could be specific to the choice of plastic size and shape and with more knowledge of their specific polymer content and degradation rates. Sensitivity analyses on other data could reveal new information regarding the assessed system. However, this would not be relevant to the thesis's focus on plastic loss.

As touched upon, the thesis entails high data uncertainty regarding inventory data and CF. However, it is considered robust enough to evaluate the new CFs' impact on the marine environment and compare the two cases. As with the interpretation of inventory results, the impact would seem more significant if the scale was bigger. For example, instead of assessing the catchment of 3.25 kg cod, looking into total cod catchment in Norway in 2021 or all global fishing, would give a higher potential loss in species.yr. Characterization factors assessing the impact of plastic in the marine ecosystem is crucial, not only for evaluating fishing gear but also for obtaining a holistic understanding of all plastic products. The current methodological gap leads to underestimations of the environmental impacts caused by plastic loss (Schwarz et al., 2019). The published SSD model includes a global map illustrating the potential impacts of entanglement, highlighting the urgent need for multinational collaboration to preserve marine biodiversity. Plastic littering is a problem that surpasses boundaries, species, and multiple jurisdictions, emphasizing the importance of collective efforts (Høiberg et al., 2022).

4.5 Methodological choices

Several methodological choices were made during this LCA, and this section will discuss their importance. First, it is worth mentioning that an LCA assesses environmental issues and typically does not assess a product's economic and social aspects (ISO, 2006), which is also the case in this thesis. Further, the LCIA in an LCA only addresses the environmental issues specified in the goal and scope definition and is affected by limitations in the LCI phase and developed characterization models (ISO, 2006).

The selection of the LCI database influences the accuracy and reliability of LCA results. In this assessment, it would have been advantageous to use a database that included emission flows of plastic to the biosphere. However, to this date, the leakage of plastic fractions has been ignored in inventory modeling and LCI databases (Boulay et al., 2021). Therefore, Ecoinvent has been used as it is the largest LCI database worldwide and is continuously updated (Wernet et al., 2016). Datasets have been used to best cover the assessment's needs and have mainly used the following geographic datasets: Europe, Europe without Switzerland, the rest of the world, and global. Norway was available for electricity, and Sweden for wood. While other databases are available, only Ecoinvent has been used to ensure consistency and avoid data overlap or redundant information that could occur using several databases. For example, databases may have variations in region-specific coverage, global average, data specialized in specific fields or industries, and fundamental structure, such as difference in modeling strategies. Further there can be differences in structure, software implementation, uncertainty, system boundaries and underlaying assumptions. (Kalverkamp et al., 2020). By exclusively utilizing the Ecoinvent database, the assessment maintains a cohesive approach and minimizes potential inconsistencies.

Ideally, an LCIA methodology with impact categories for plastic impacts on the marine environment would have been preferred, but such a methodology does not currently exist. The ReCiPe2016 method was selected as the LCIA method. ReCiPe is widely used in Europe and is based on up-to-date data and methodologies derived from current scientific knowledge (Huijbregts et al., 2016). The method offers midpoint and endpoint assessment levels, and both have been used in this thesis. However, it is important to note that only a few selected impact categories were assessed at the two levels. For instance, at the endpoint level, this assessment focused solely on ecosystem quality using species.yr to measure impacts. Another LCIA method, such as the regionalized LCIA method LC-IMPACT, could have presented the endpoint results in PDF (potentially disappeared fraction of species) (Verones et al., 2020). However, the current version of the AB/Brightway 2 software used in this thesis does not incorporate the method. Differences between LCIA methods can arise due to variations in underlying classification, characterization models, and versions used for categories or subcategories, reference units, and their implementation. Additionally, the depth of characterization can differ between methods (Koch et al., 2022). These variations can lead to different weights assigned to different life cycle stages, processes, or emissions, ultimately influencing the magnitude and distribution of environmental impacts in the assessment results.

The ReCiPe2016 method encompasses impact categories from three cultural perspectives: egalitarian, hierarchist, and individualist. In this assessment, the hierarchist perspective was chosen as the basis for the analysis, as it is the mean perspective and is based on a scientific consensus regarding the timeframe and plausibility of impact mechanisms (Huijbregts et al., 2016). For the impact category of climate change, the choice of cultural perspective has implications for the time horizon used in calculating the GWP. For the hierarchical perspective, a timeframe of 100 years is employed when considering GWP (Hauschild & Huijbregts, 2015). The cultural perspectives for certain impact categories can also influence the transitions from the midpoint to the endpoint level. For instance, the cultural perspective affects the transition factor for *climate change* in relation to terrestrial and freshwater ecosystems. However, factors such as acidity and toxicity for terrestrial, freshwater, and marine maintain the same values across cultural perspectives (Huijbregts et al., 2016).

4.6 Further research

The present LCA study has been conducted to address the knowledge gap regarding the impacts of plastic on the marine environment within the field of LCA. While this assessment provides insights, it also reveals uncertainties and identifies additional knowledge gaps, highlighting the need for further research to comprehensively address the impacts of marine plastics and fisheries. In addition, it is important to note that the results could be altered if more certain data were used, such as direct contact with fishermen, producers, or conducting tests.

The first topic that requires further research is quantifying plastic loss to the marine environment. There is a need for new and detailed analysis of fishing gear equipment with high loss rates and uncertainties connected to them (Syversen et al., 2020), littering from fishing vessels, and additional plastic flows reaching the marine environment. Further, the thesis has assumed that the environmental compartment of direct plastic loss to the ocean is 100%. Further research should address the potential fractions of plastics collected, reaching beaches, floating, or sinking to the seabed, emphasizing Norwegian conditions.

Further research is also needed to address the uncertainties surrounding vessel maintenance and loss of marine coating, which was the second-highest loss for both cases. The newest identified literature addressing microplastic loss from marine paintings in Norway is about ten years old, and therefore the assessments assumed loss rate and polymer content could be outdated.

The current inventory in this thesis has excluded potentially essential processes, such as by-product utilization, consumption, and end-of-life treatment. Further research should include them to provide a more comprehensive understanding of the system. Winther et al. (2009) indicated central data that should be collected, standardized, and made available upon request or public for LCA practitioners and the industry to undertake a robust and data-driven assessment of seafood products. However, Winther et al. (2020) state that little has changed since 2009 regarding data availability. Further, their assessment entails uncertainties, and they would like more data concerning product loss, fuel consumption, fishery refrigeration, and by-product utilization. Further, this thesis includes the final environmental compartment for tire wear and plastic pellets. There should be further investigation, and country-specific environmental compartment rates should be addressed, given Norway’s significant coastline.

There is a need for conducting LCAs on a broader range of gear types and species in the fishing industry, as this will provide a more extensive assessment of the environmental impact associated with fishing practices. Additionally, it could be recommended to assess other major fishery nations to gain a global perspective on the impacts of marine plastics.

The field of LCIA methodology has seen developments, including the preliminary CF used in this LCA. However, continued work on the methodology is crucial to improve the accuracy and completeness of developed factors, address missing factors, close inventory gaps, and improve methodologies. Further research is needed to close the gap regarding LCA impact categories focusing on marine ecosystems and drivers of marine biodiversity loss. When available in the established methods, it could become more accessible for LCA practitioners to assess the environmental issue assessed plastic loss from fishing activities.

5 Conclusion

The accumulation of marine plastic debris poses a growing threat to the oceans, resulting in millions of marine animals' debilitation, mutilation, and mortality annually, showing the need to assess such threats. LCA is one well-established method to quantify the impacts of products. However, it was initially developed to assess land-based products and therefore lack impact categories focusing on marine ecosystems and drivers of marine biodiversity loss. Work is currently being done to close the methodological gap regarding marine plastic impacts, with the newly developed CF for macroplastic entanglement and tire wear microplastic. The assessment has evaluated and compared the environmental impact of one kg cod filets without skin and bones transported to the wholesaler/retailer, caught with either demersal trawl or set gillnet. Established impact categories at the endpoint level for ecosystem quality have been assessed, in addition to the characterization factor for entanglement and tire wear.

Inventory results addressed plastic flows and showed that catching cod with trawl required 20.33 grams more plastic per functional than set gillnet. Further, results showed that plastic loss to the marine environment was 0.41 grams greater per functional unit for trawl. In both cases, the largest losses are caused by fishing gear, followed by marine coating from vessels. Trawl exhibits the highest loss, except for the loss of macroplastic, where gillnet loss was 0.09 grams greater. These findings can provide insight into mitigation strategies addressing marine plastics and potentially reduce inventory data gaps.

LCIA results have been evaluated at the midpoint and endpoint levels and show that gillnet is the least damaging catchment method except for entanglement. Tire wear was equal for both cases. The highest potential loss in species.yr is attributed to terrestrial impact categories, and marine impact categories show low impacts, emphasizing the need for additional life cycle impact assessments and inventory links to the marine environment. Results showed that species.yr loss due to entanglement was lower than impacts caused by tire wear. The new categories' potential impact is significantly smaller than the established ones. However, the thesis entails high uncertainty and limitations.

Further research and quantitative analysis are needed regarding fishing gear, plastic loss to the ocean, marine coatings, final environmental compartments, and methodologies. Further, excluded processes should be included, and the LCA study should be expanded to more gear types, species, and countries. Closing these gaps will enhance the understanding of fishing activities and plastic’s environmental impact and support mitigation strategies. The work with this thesis, additional assessments, and research can contribute to closing the current knowledge- and data gap concerning marine plastics and their impacts on Norwegian marine ecosystems, which currently limits Norwegian fisheries in meeting goals set by the United Nations.

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7 Appendix

Appendix 1 Assumptions and calculations for vessels using set gillnet.

	Value	Unit	Reference/calculation	Comment
Coastal vessel catching cod south of 62 degrees	9	vessels	(Fiskeridirektoratet, 2022f)	
Coastal vessels catching cod, haddock, and saithe north of 62 degrees	1424	vessels	(Fiskeridirektoratet, 2022f)	
Cod caught with set gillnet	80 590	ton	(Fiskeridirektoratet, 2022e)	
Cod, haddock, and saithe caught in 2021 with conventional coastal gear[a]	283 492	ton	(Fiskeridirektoratet, 2022e)	Of this, 28.4% were cod captured with set gillnet. (80 590/283 492)
Cod caught with conventional coastal gear[a]	186 859	ton	(Fiskeridirektoratet, 2022e)	Of this, 43.1% were cod captured with set gillnet. (80 590/186 859)
Vessels south of 62 degrees catching cod with set gillnet	4	Vessels	Calculation: $9\ vessels \cdot 43.1\%$	Rounded up to the closest integer. The percentage for the catch is assumed to be the same south of 62 degrees.
Vessels north of 62 degrees catching cod with set gillnet	405	Vessel	Calculation: $1424\ vessels \cdot 28.4\%$	Rounded up to the closest integer. The percentage for the catch is assumed to be the same north of 62 degrees.
Total Norwegian vessels catching cod with set gillnet	409	Vessel	Calculation: $4 + 405$	

[a] Conventional coastal gear in this assessment is limited to gillnets and seines, hook gear is not included as this is typically used in deep waters.

Appendix 2 Conversion of unit, from PDF to species.yr

PAF/kg/m2 -> PAF*m2/kg		
CF macroplastic debris entanglement (Release point: Tromsø, runtime = 1 year)		
unit	**value**	**comment**
PAF*m2*yr/kg	4,18E-09	Average CF 1 year after a release of a plastic emission from the west coast of Tromsø
PDF*m2*yr/kg	2,09E-09	conversion step from PAF to PDF, assuming 1:0.5 to be in line with Corella-Puertas 2022
PDF*m3*yr/kg	2,09E-07	conversion step from m2 to m3, taking 200 m for global seawater depth (Fantke et al. 2018 from Corella-Puertas 2022)
species/m3	3,45E-12	average species density per m3 in marine ecosystems (Recipe 2016)
species.yr/kg plastic	7,21E-19	CF value for use with Recipe
CF microplastic physical impact (not spatial)		
unit	**value**	**comment**
PDF*m2*yr/kg	2,30E-02	endpoint CF for road wear particles Corella-Puertas et al. 2022
PDF*m3*yr/kg	2,30E+00	conversion step from m2 to m3, taking 200 m for global seawater depth (Fantke et al. 2018 from Corella-Puertas 2022)
species/m3	3,45E-12	average species density per m3 in marine ecosystems (Recipe 2016)
species.yr/kg plastic	7,94E-12	CF value for use with Recipe

Appendix 3 Full inventory per FU for the case with demersal trawl

Inventory per FU - Demersal trawl			
Process	Parameter	Data	Unit/FU
Input from technosphere			
Fishing gear materials	Ethylene vinyl acetate copolymer production, RER	0,96	g
	Polyethylene production, high density, granulate, RER	13,95	g
	Synthetic rubber production, RER	9,63	g
	Metal working, average for steel product manufacturing, RER	15,05	g
Vessel operation and maintenance	Trawl construction, steel, GLO	115,04	g
	Trawl maintenance, steel, GLO	115,04	g
	Diesel, burned in fishing vessel, GLO	0,96	kg
Processing	Building construction, hall, RoW (inactive)	1,81E-05	m2
	Freshwater input	0,02	m3
	Soap production, RER (inactive)	0,98	g
	Detergent: cleaning consumables, without water, in 13.6% solution state, GLO	1,24	g
	Metal working machine production, unspecified, RER (inactive)	0,75	g
	Wood: softwood forestry, pine, sustainable forest management, SE	0,81	g
	Electricity production, hydro, reservoir, alpine region, NO	1,18	kWh
	Diesel, burned in building machine, GLO	0,42	ml
	Packaging for sale: polypropylene production, granulate, RER (inactive)	50,00	g
	Packaging for transportation: corrugated board box production, RER (inactive)	80,00	g
	Packaging for transportation: packaging film production, low density polyethylene, RER	0,01	g
Transportation	Transport, freight, lorry with refrigeration machine, 7.5-16 ton, EURO6, R134a refrigerant, freezing, GLO	1,34	tkm
Emissions to biosphere			
	Marine coating, plastic loss to the environment	0,314	g

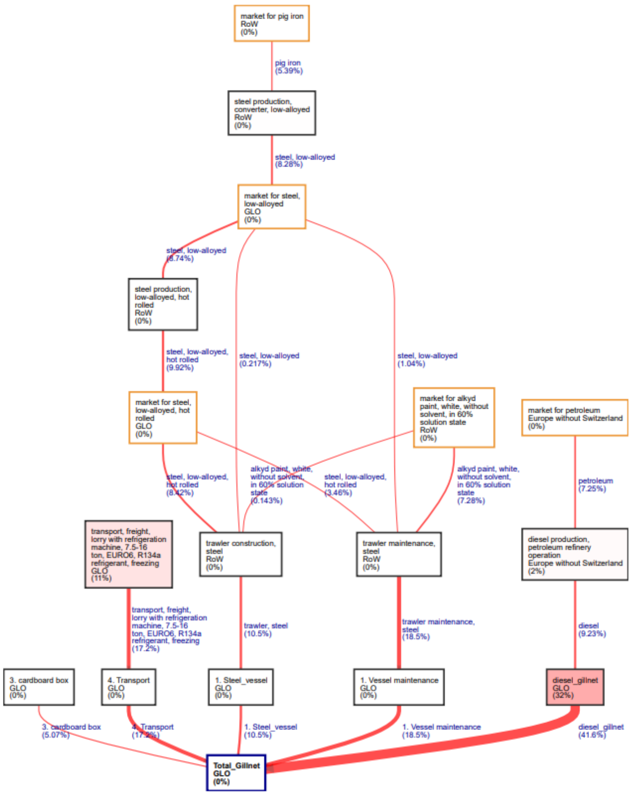
Vessel operation and maintenance	Refrigerant, emission HFC	0,023	g
	Co2	3028,94	g
	SO2	1,10	g
	CH4	0,22	g
	NOX	41,81	g
	CO	2,77	g
	NMVOC	2,29	g
Fishing activity	Synthetic rubber loss	0,57	g
	Polyethene (PE) loss	0,039	g
	Macro: PA	0,025	g
	Macro: PP	0,033	g
	Macro: PE	0,217	g
Transport	Tire abbreviation	0,04	g
Plastic pellets	Loss from plastic pellet production	0,03	g

Appendix 4 Full inventory per FU for the case with set gillnet

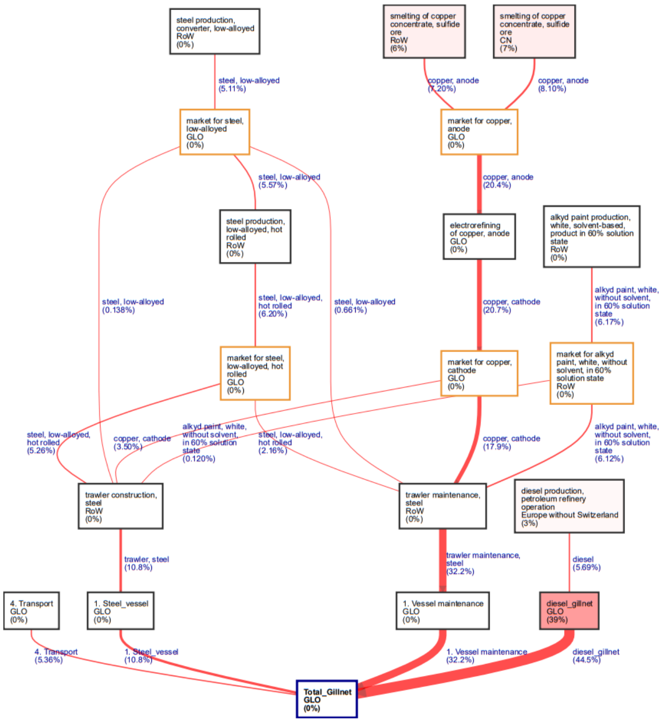
Inventory per FU - Set gillnet			
Process	Parameter	Data	Unit/FU
Input			
Fishing gear materials	Polypropylene production, granulate, RER (inactive)	0,70	g
	Polyethylene production, high density, granulate, RER (inactive)	0,26	g
	Primary lead production from concentrate, GLO (inactive)	1,74	g
	Nylon 6-6 production, RER	3,63	g
	Polyester fibre production, finished, RoW (inactive)	0,06	g
	Gravel and sand quarry operation, RoW (inactive)	23,07	g
Vessel operation and maintenance	Trawl construction, steel, GLO	96,14	g
	Trawl maintenance, steel, GLO	96,14	g
	Diesel, burned in fishing vessel, GLO	0,25	kg
Processing	Building construction, hall, RoW (inactive)	0,00002	m2
	Freshwater input	0,02	m3
	Soap production, RER (inactive)	0,98	g
	Detergent: cleaning consumables, without water, in 13.6% solution state, GLO	1,24	g
	Metal working machine production, unspecified, RER (inactive)	0,75	g
	Wood: softwood forestry, pine, sustainable forest management, SE	0,81	g
	Electricity production, hydro, reservoir, alpine region, NO	1,18	kWh
	Diesel, burned in building machine, GLO	0,42	ml
	Packaging for sale: polypropylene production, granulate, RER (inactive)	50,00	g
	Packaging for transportation: corrugated board box production, RER (inactive)	80,00	g
	Packaging for transportation: packaging film production, low density polyethylene, RER	0,01	g
Transportation	Transport, freight, lorry with refrigeration machine, 7.5-16 ton, EURO6, R134a refrigerant, freezing, GLO	1,34	tkm
Output			
	Marine coating, plastic loss to the environment	0,262	g

Vessel operation and maintenance	Refrigerant, emission HFC	0,026	g
	Co2	778,87	g
	SO2	0,28	g
	CH4	0,06	g
	NOX	10,75	g
	CO	0,71	g
	NMVOC	0,59	g
Fishing activity	Polypropylene (PP), material loss	0,05	g
	Polyethene (PE), material loss	0,02	g
	Nylon (PA), material loss	0,11	g
	Polyester, material loss	0,004	g
	Macro: PA	0,34	g
	Macro: PP	0,03	g
Transportation	Tire abbreviation	0,04	g
Plastic pellets	Loss from plastic pellet production	0,02	g

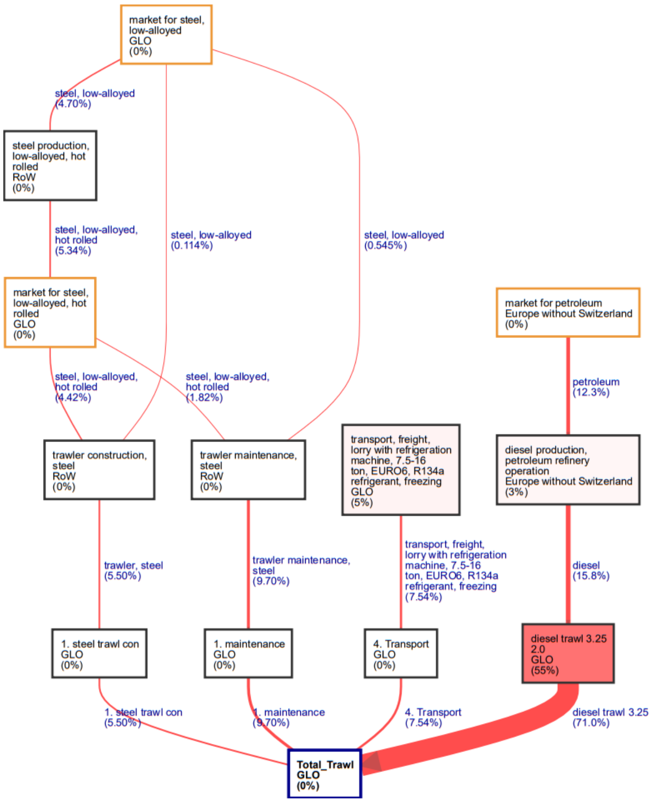
Appendix 5 Sanky diagrams



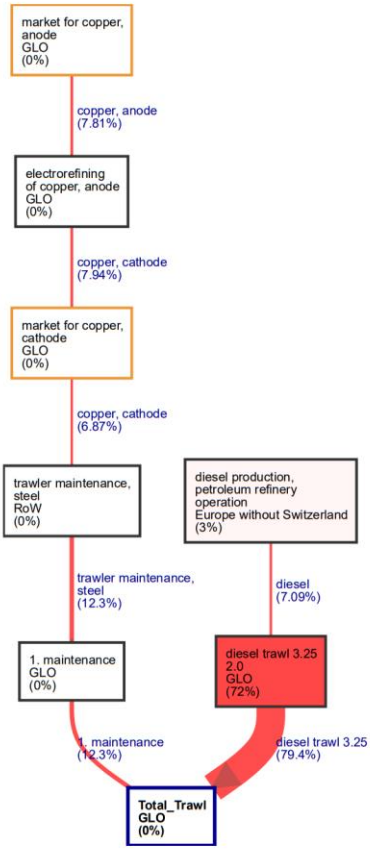
Sanky diagram 1 Endpoint, climate change terrestrial ecosystem for the case with gillnet.



Sanky diagram 2 Endpoint, acidification terrestrial for the case with gillnet.



Sanky diagram 3 Endpoint, climate change terrestrial ecosystems for the case with trawl



Sanky diagram 4 Endpoint, acidification terrestrial for the case with trawl.

Appendix 6 Inventory data and calculation

Collected inventory data with references, assumptions, and inventory calculations per FU can be seen in the Excel file named *Inventory data and calculations.*

Appendix 7 Results from AB

Results loaded down from AB at the midpoint and endpoint level for process contribution with a cut-of-level at 6.3% can be seen in the Excel file named *Results from AB.*

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