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International Reference Centre for the Life Cycle of Products, Processes and Services

FINAL REPORT

MARINE PLASTIC LITTER AND OTHER OCEAN THREATS – A LITERATURE REVIEW IN THE CONTEXT OF LIFE CYCLE ASSESSMENT

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WARNING

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Scientific Direction

Disclaimer

This report reviewed the scientific literature in order to identify research needs for the integration of marine plastic litter within the life cycle assessment framework. It first put this environmental stressor into perspective with the other threats to ocean health by mapping them. It showed that human activities are negatively affecting oceans in many different ways.

Although this may be perceived by some readers as an attempt to diminish the importance of marine plastic litter – a subject that has been much covered by mainstream media in the past few months – this is not the intention of the authors. They have reported what is present in the scientific literature at this time.

Summary

In the context of recent concerns over plastic accumulation in marine habitats, this report reviewed the scientific literature on marine plastic litter and other threats to oceans' health. It aimed to put marine plastic litter into perspective with other threats to ocean health and to identify the research needs for its integration within the LCA framework.

A total of 205 publications from the bibliographic search were selected. Based on the most relevant ones, 11 ocean threat categories were identified: ocean acidification, climate change, non-human diseases, marine eutrophication, marine litter, noise, overfishing, physical habitat destruction, pollutants, species introduction, and UV radiation. Each category was described in terms of its mechanism (impact pathway). This showed that humans affect the oceans in very diverse ways, through different mechanisms and at different scales. Only a few publications compare those threats in a comprehensive way and there is no consensus as to what the most important ones are. As marine plastic litter is only covered by a few of the most recent scientific publications on ocean threats, its importance cannot be confidently assessed.

The inclusion of marine plastic litter in LCA was also discussed. Significant research still needs to be done to obtain robust plastic fate factors that link leakage in the environment and concentration in habitats accounting for plastic type, shape, and degradation. Even more work is needed to model effects on ecosystems since no effect factors have been proposed in the literature yet. Finally, microplastics are clearly one of the least understood aspects of marine litter and are the source of rising concerns in the recent scientific literature.

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Glossary

Anoxic	Without oxygen
Benthic	On the sea floor
CCS	Carbon capture and storage
CFC	Chlorofluorocarbon
Demersal	On the sea floor
GHG	Greenhouse gas
Hypoxic	With little oxygen
LCA	Life cycle assessment
LCIA	Life cycle impact assessment
PAH	Polyaromatic hydrocarbon
PCB	Polychlorinated biphenyl
Pelagic	Related to the open ocean
POP	Persistent organic pollutant
SST	Sea surface temperature
UV	Ultra-violet

1 Introduction

The issue of marine plastics litter has attracted significant public attention in recent years. There is a growing realization that a fraction of plastics produced by humanity is deliberately or accidentally littered and ultimately ends up in the oceans. The fate of littered plastic objects differs depending on their form, composition and littering location and will consequently have different effects on ecosystems and possibly human health. Among these, plastic bags are known to affect fauna by entanglement or ingestion. Moreover, plastic objects decompose into small fragments over time, can accumulate in sediments, and be ingested by animals, some being part of the human food chain.

While some may consider this as the environmental issue of the day, going as far as calling our contemporary era as the "Plastic Age", current tools and frameworks for environmental assessment are not necessarily equipped to take it into consideration. Such is the case of Life cycle assessment (LCA), which does not include the threat of marine plastics littering in its current framework.

LCA is a product-level assessment tool that compares products based on their life cycle potential environmental impacts. Multiple environmental stressors are assessed, covering common environmental issues related to human health and ecosystem quality, such as climate change, human toxicity, ozone layer depletion, aquatic ecotoxicity, freshwater eutrophication, terrestrial acidification, etc. However, most of those stressors concern land-based impacts and marine impacts are generally underrepresented (Woods et al., 2016). According to those authors, eutrophication-induced hypoxia and overfishing indicators could readily be included in life cycle impact assessment (LCIA) methodologies and climate change, ocean acidification and seabed damage would only require some improvements in models to provide more robust values. However, marine plastic litter still requires important developments.

Before looking at what the scientific literature says about the research needs to achieve the integration of marine plastic litter within the LCA framework, we first put this stressor into perspective with the many threats faced by the oceans.

Therefore, the goals of this project are:

To carry out a scientific literature review on marine plastic litter and the main threats to ocean health in order to:

- **Put marine plastic litter into perspective with other threats to ocean health by:**
  - **Identifying the main threats and describing their impact pathway (origin and environmental consequences);**
  - **Reporting on studies evaluating their importance;**
- **Identify the research needs for the integration of marine plastic litter within the LCA framework.**

The content of this report is divided into the following sections: first, the bibliographic search methodology is described, along with a summary of the selected publications. Then, marine plastic litter is put into perspective with the other threats to ocean health by first describing each of those threats and then reporting on what the literature says about their relative importance. Finally, the research needs for the integration of marine plastic litter in LCA are presented.

2 Bibliographic Search Methodology

The bibliographic search for this project has first been carried out with the keyword "ocean pollution impacts", limiting the results to the following criteria:

- Document types:
  - Scientific papers
  - Reports
  - Technical reports
  - Books
  - Theses
  - Magazine articles
- Date: From 2000 to today
- Fields (19):
  - Oceanography
  - Environmental science
  - Ecology
  - Biology
  - …[1]
- Subjects (~100):
  - Marine
  - Environmental impacts
  - Oceans
  - Marine and freshwater biology
  - …[2]

This search query identified 237 publications. After going through each title and abstract, 158 were selected and classified in 13 categories:

1. Acidification
2. Climate change
3. Diseases
4. Eutrophication
5. General
6. Marine litter
7. Noise
8. Overfishing
9. Physical habitat destruction
10. Pollutants
11. Species invasion
12. UV radiation
13. Other

[1] Complete list in appendix
[2] *Ibid.*

Those results show the diversity of ocean threats. The "General" category includes publications on several ocean threats and, in some cases, their relative importance. Subsequent specific searches were carried out to refine the assessment of each category pushing up the total selected publications to 205.

3 Marine Plastic Litter Put into Perspective with the Other Threats to Ocean Health

3.1 Threats to ocean health

The second step of the literature review was the assessment of the selected publications. Due to time constraints, only a smaller number of publications, chosen according to their relevance, were analyzed in more detail, prioritizing the publications in the “General” category, which cover several ocean threats. This review led to the description of each threat in the following sections. For each, a cause-effect chain figure has been drawn with concepts and arrows. The arrows represent links documented in the analyzed literature, rather than all existing links. Dashed lines represent probable links, not explicitly cited in the analyzed literature.

3.1.1 Acidification

Acidification of the oceans is the decrease of ocean water pH mainly due to the increase of CO_2 concentration in the atmosphere and its dissolution in water producing carbonic acid. Every year, approximately 7 Gt of CO_2 is absorbed by the oceans from the atmosphere (Le Quéré et al., 2016). Although surface water warming due to climate change decreases CO_2 solubility, this is unlikely to counter the effect of increased CO_2 atmospheric concentration on ocean concentrations (Doney et al., 2014). Nitrogen and sulfur oxides emissions to air, e.g. from sea transport, also contribute to ocean acidification (Hassellöv et al., 2013). Leakage from carbon storage in geological formations is regarded as a potential source of local acidification in the future (Widdicombe et al., 2013).

Ocean acidification occurs globally. Impacts on foraminifera (Kuffner et al., 2008), vertebrates (Briffa et al., 2012), plankton (Armaroli and Balzani, 2011; Strong et al., 2014), mollusks (de Vries, et al., 2013), and crustaceans (Briffa et al., 2012) are mentioned in the literature and studies on its impacts on coral (Kuffner et al., 2013), abalones (Li et al., 2013), sponges (Wisshak et al., 201), oysters (Li et al., 2014), cockles (Li et al., 2014), cod (Frommel et al., 2012), crustacean and fish larvae (Lecchini et al., 2017), coralline algae (Kuffner et al., 2008), and urchins (Figueiredo et al., 2016; Miles et al., 2007; Wolfe et al., 2013) have been found. The first threat to the fauna is decalcification. Coral exoskeleton, plankton and mollusk shells are composed of different forms of calcium carbonate, which are soluble in acidic water. Those species are therefore vulnerable to ocean acidification. Coral reefs being home to a great number of species, their death has a negative effect on them too. Moreover, water pH plays an important role in chemical signals used by the marine fauna. A change in pH could affect behavior like reproduction and the search for a suitable habitat (Lecchini et al., 2017). Shi et al. (2010) showed that ocean acidification may decrease iron bioavailability for phytoplankton. Some species may not be affected (Golbuu et al., 2016), but it is recognized that the effects of acidification on marine ecosystems are not well known (Rockstrom et al., 2009).

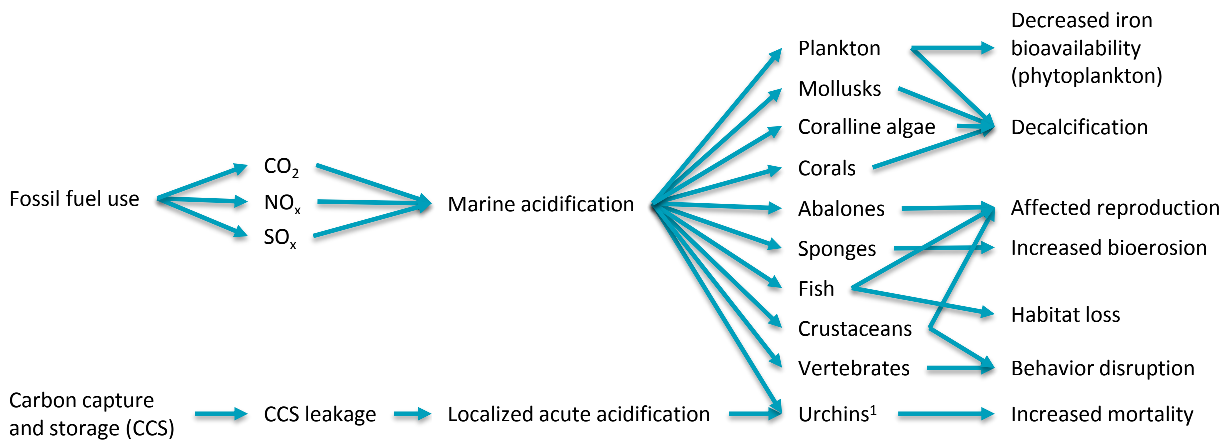

Figure 3-1: Marine acidification cause-effect chain.

3.1.2 Climate Change

GHG emissions from all sectors of the economy have numerous consequences on the climate that affect oceans globally: e.g. water warming, reduced oxygen concentration, marine ice cover change, sea level rise, weather effects (changes in wind, precipitation, and runoff patterns) and ocean current disruption.

According to the IPCC (Portner et al., 2014), increasing air and water temperatures affect many marine species and ecosystems in their abundance, geographic distribution, migration patterns, and timing of seasonal activities. For example, many fish, invertebrate, and phytoplankton species have already migrated to cooler habitats closer to the poles or in deeper waters. The authors point out that based on past natural climate change, significant negative ecosystem shifts are expected in the future, resulting in species extinctions.

Many studies investigated consequences of increased water temperature on coral reefs (Sheppard et al., 2001; Kuffner et al., 2013; Fitt et al., 2001), which are also affected by acidification. Water warming contributes to coral "bleaching" by causing the release of the symbiotic algae essential to its good health (Fitt et al., 2001). Unprecedented coral bleaching was observed in the Great Barrier Reef in 2016 and was attributed mainly to warming waters (Griffith, 2016). Sea urchins are also negatively affected according to Wolfe et al. (2013).

Another problem related to increased sea water temperature mentioned in the literature is reduced dissolved oxygen levels in ocean waters as it could mean expanded hypoxic, with low oxygen, and anoxic, without oxygen, zones (Shaffer et al., 2009; Portner et al., 2014) and lower overall ocean biological productivity (Doney et al., 2014). According to Altieri and Gedan (2014), changes in water temperature, ocean acidification, sea-level rise, precipitation, wind, and storm patterns exacerbate hypoxic zones (see section 3.1.4), by affecting oxygen availability and ecological responses to hypoxia.

Sea-level rise concerns coastal ecosystems and could affect corals, sea turtles, mangroves and fish stocks (Fuentes et al., 2010; Portner et al., 2014). Marine ice cover, a habitat for different species such as mammals (e.g. polar bears, seals) is also becoming scarcer year after year (O'Shea and Odell, 2008).

The potential impact of climate change on ocean currents is also cause for alarm. The global conveyor belt, i.e. the worldwide density-driven ocean current, is crucial to climate regulation and its modification

[3] More species than urchins may be affected.

(e.g. slow-down) caused by an increased freshwater input in the North-Atlantic could have major global impacts to an extent that is not well understood (Armaroli and Balzani, 2011).

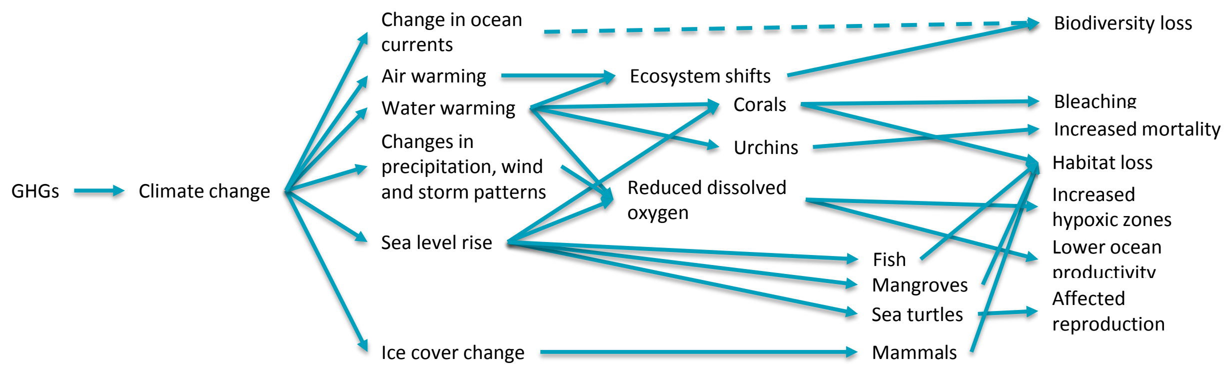

Figure 3-2: Climate change cause-effect chain.

3.1.3 Diseases

Many anthropogenic factors can trigger disease or parasite outbreaks in marine species. Aquaculture is identified in the literature as a transmission vector for parasites in surrounding mollusk populations (Lafferty et al., 2004), like shell disease, and fish populations (Torrissen et al., 2013), like salmon lice. Moreover, mammals are potentially affected by pathogens and parasites carrying runoffs from land-based activities (Lafferty et al., 2004). Climate warming is likely to aggravate the impact of most pathogens according to Harvell et al. (2002).

Figure 3-3: Diseases cause-effect chain.

3.1.4 Eutrophication

This environmental issue is linked to the abundance of nutrients, mainly phosphorus and nitrogen, in a water body. Nutrients enter the oceans through runoffs from land-based activities. Fertilizers used in agriculture and organic matter in domestic and industrial sewage are examples of nutrient sources (Boyle, 2017; Strain & Macdonald, 2002). Also, coastal forestry, e.g. mangrove deforestation, increases soil losses, which also contain nutrients. Ocean dumping of sewage sludge and dredging spoils (Ahnert & Borowski, 2000), pelagic litter and sewage from ships (de Sylva et al., 2000), and aquaculture (Karakassis et al., 2002) are also sources of nutrients for the oceans. Airborne nitrogen nutrients can also end up in the ocean (Boyle, 2017; Luo et al., 2014). Nitrogen is emitted to air as nitrogen oxides from fossil fuel combustion (e.g. transportation and power plants) and ammonia from fertilizer use in agriculture. This airborne nitrogen is eventually deposited back on the ground or on water.

The abundance of nutrients in water leads to eutrophication. Phytoplankton, algae and other plants consume them and thrive. As a consequence, water becomes less transparent. Algae eventually bloom, accompanied by many adverse effects: they block sunlight for other species below the surface potentially affecting benthic organisms and, in some cases, produce toxins. Dead organic matter accumulates on the bottom and is decomposed by microorganisms. The increased microbial activity consumes the oxygen in the water to a point where hypoxic or anoxic regions are created (Kitsiou &

Karydis, 2011). Oxygen being essential to marine life, these zones become dead. Global warming amplifies this effect of eutrophication because of the reduced oxygen solubility in water (Altieri & Gedan, 2014).

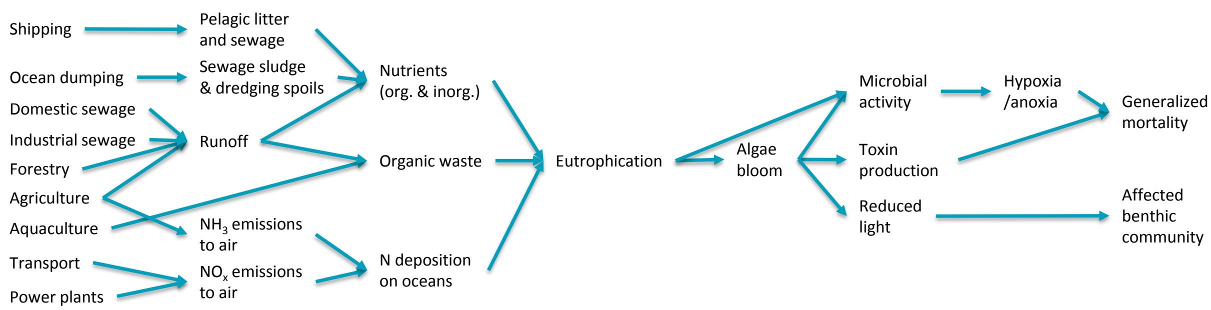

Figure 3-4: Eutrophication cause-effect chain.

3.1.5 Marine Litter

Marine litter is mainly composed of plastic. Once in nature, plastic is persistent and is carried by wind and rivers until it reaches the ocean (Law, 2017). Land-based sources of plastic are packaging waste, microbeads in cosmetics, microfibers from washing synthetic clothes, tire particles, and unprocessed plastic granulates (Andrady, 2011; Boucher & Friot, 2017). They constitute approximately 80% of plastics in oceans (Andrady, 2011). At sea, ships are a source of marine litter, including abandoned or broken fishing equipment, “ghost nets”, and cellulose from paper (de Sylva et al., 2000; Hong et al., 2014; Wilcox et al., 2013; Angiolillo et al., 2015).

The mass of plastic in the oceans is discussed in many publications. The Ellen MacArthur Foundation (2016) estimated that 25 Mt per year of plastic packaging escapes collection systems, part of it ending up in the oceans. According to Jambeck et al. (2015), between 4.8 and 12.7 Mt of plastic waste entered the oceans in 2010. Those numbers do not include primary microplastics (plastic entering the oceans as microparticles <5 mm in size, or similar depending on the source), which are estimated between 0.8 and 2.5 Mt per year (Boucher & Friot, 2017).

Depending on the plastic material, debris will either sink or float. Between 0.1 and 0.27 Mt floats on the oceans’ surface according to Cózar et al. (2014) and Eriksen et al. (2014). Fish, reptiles, mammals and birds can eat the debris, clogging their digestive tract, or get entangled in or choked by bigger pieces even in the most remote regions in the world (Gall & Thompson, 2015; Hoarau et al., 2014; Trevail et al., 2015; Verlis et al., 2013; Vendel et al., 2017; Nicolau et al., 2016). Under the action of a wide range of mechanisms, plastics eventually disintegrate into very small pieces (secondary microplastics) and can be ingested by large and small organisms (Zharikov, 2013). The toxicity of those microplastics is not well known. While the ecotoxicity of non-polluted microplastics (i.e. without pollutants adsorbed on their surface) is not clear, toxic substances, like PCB, tend to adsorb on them and could affect organisms ingesting the plastics (Andrady, 2011; Cole et al., 2011).

As the world plastic production increases over the years, if comprehensive waste management schemes are not put in place, plastic debris in the oceans will increase too (Rochman, 2015). The Ellen MacArthur Foundation (2016) estimated that, in 2050, the world plastic production will quadruple and there will be five times more plastic in the oceans.

In response to the issue of plastic non-degradability in nature, a variety of degradable plastic packaging are available on the market. Oxodegradable plastics contains an additive allowing the material to fragment into particles under the effect of the sun and oxygen. Although it was initially believed that those particles would then biodegrade, a British study concluded that they actually do not or if they do, it is at a very slow rate (Thomas et al., 2010). Therefore, oxodegradable plastics are a source of microplastics and were the object in 2017 of a ban proposal by more than 150 organizations[4]. Starch-polymer plastics are labeled as biodegradable, but only the starch part does biodegrade, releasing microplastics into the environment from the polymer part (Andrady, 2011; Coll et al., 2011). Some plastics, biosourced or not, do degrade naturally in the environment (Andrady, 2011; Mohee et al., 2007; O'Brine & Thompson, 2010). More research is needed to clearly understand the behavior of (degradable) plastics in the environment in general, and in the oceans in particular, taking into consideration: polymer type, size and shape, environmental conditions (floating on the sea surface, buried, shoreline etc.).

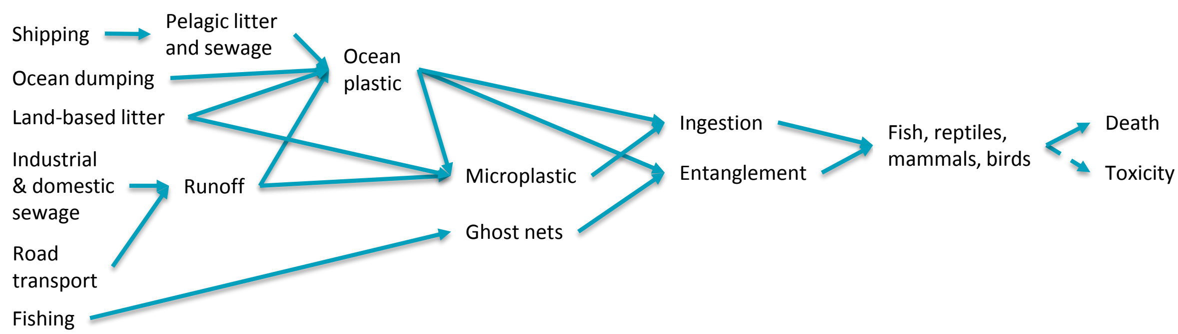

Figure 3-5: Marine litter cause-effect chain.

3.1.6 Noise

Water conducts acoustic waves much better than air. Therefore, noise from natural phenomena or human activities, e.g. shipping, military, resource exploration, oil and gas drilling, and offshore mining, can be heard over a very long distance (Kaplan & Mooney, 2015; Weilgart, 2007). Global economic and coastal population growth generate more human coastal and pelagic activities, which in turn generate more underwater noise. Sensitive species to this stress are fish and mammals, for which behavioral changes are observed, e.g. during reproduction (Moretti et al., 2014; Weilgart, 2007). Noise events can have more serious consequences like fish hearing loss and whale strandings and mortality (Moretti et al., 2014; Weilgart, 2007). However, some tolerance to noise was observed with whales and European sea bass (Radford et al., 2016; Weilgart, 2007).

[4] https://newplasticseconomy.org/news/over-150-organisations-back-call-to-ban-oxo-degradable- plastic-packaging

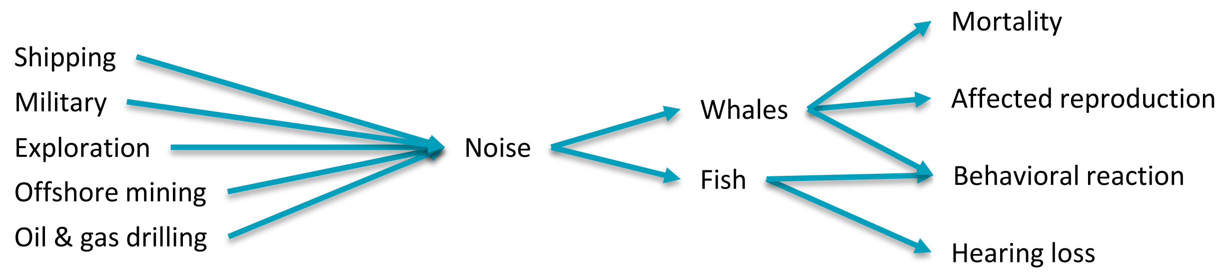

Figure 3-6: Noise impacts cause-effect chain.

3.1.7 Overfishing

Overfishing happens when the catch rates are higher than the fish population growth rates. There is evidence that most of the commercial fish species are being overfished globally. According to Coll et al. (2008), the world total catch per capita is at least twice the sustainable level. Over a 50-year period, large predatory fish populations have decreased by 90% (Sala & Knowlton, 2006).

Adverse effects of overfishing are multiple and extensive: decreased fish size, disappearing fish species, removal of mature stock, change in community structure, decreased food availability, and change in trophic interactions (Coll et al., 2008; Sala & Knowlton, 2006; de Sylva et al., 2000; Jackson et al., 2001). Fishing also affects other species through by-catch, which highly depends on fishing methods (Halpern et al., 2008; Woods et al., 2016). Collisions with ships is an issue for large marine mammals such as whales. It may lead to the death of the animal, sometimes a member of an already vulnerable population (O'Shea & Odell, 2008).

Fishing impacts related to marine litter (e.g. ghost nets) and physical habitat destruction (e.g. trawling) are not included in this category.

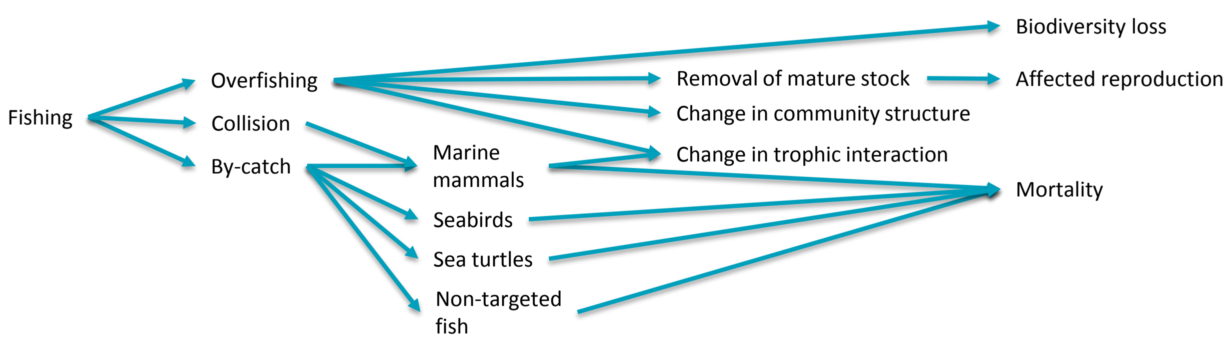

Figure 3-7: Overfishing cause-effect chain.

3.1.8 Physical Habitat Destruction

Loss of habitat is one of the main reasons for concern regarding global biodiversity. Activities such as offshore mining, dredging, coastal development, and mangrove deforestation cause the direct destruction of habitats (Bullerie & Chapman, 2010; de Sylva et al., 2000; Kim & Grigalunas, 2009; Richard & Friess, 2016; Waycott et al., 2009). Among mining activities, extraction of sand for concrete production is described as having negative impacts on marine habitats (Freed & Granek, 2014; Hwang et al., 2014; Jonah et al., 2015). Other activities related to sedimentation cause habitat destruction indirectly: activities causing sediment runoffs like forestry and agriculture (Lough et al., 2015); activities producing sedimentation like aquaculture (Brooks et al., 2004); activities causing the mixing of sediments, resulting in increased turbidity and sediment redeposition such as mining (Thiel, 2001; Ahnert & Borowski, 2000), affecting the benthos and blocking sunlight. Trawling and blast fishing affect entire ecosystems by habitat destruction (Sala & Knowlton, 2006).

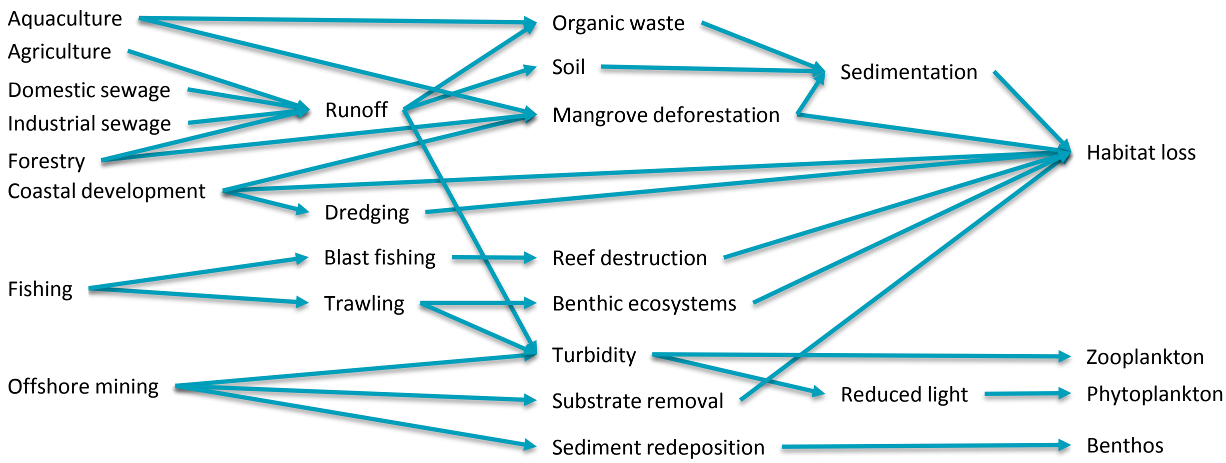

Figure 3-8: Physical habitat destruction cause-effect chain.

3.1.9 Pollutants

The problem of ocean pollutants is very complex due to the very high diversity of chemicals emitted into the ocean by land or ocean-based human activity. It is estimated that 80% of marine pollution comes from land (Hennig, 2010). Major sources of ocean pollutants are, among others, runoff from agriculture (Halpern et al., 2008; Lough et al., 2015), industrial and domestic sewage (Halpern et al., 2008), litter and sewage from ships (de Sylva et al., 2000), ocean dumping of sewage sludge and dredging spoils (Ahnert & Borowski, 2000), munitions (Szarejko & Namieśnik, 2009), radioactive waste (Livingston & Povinec, 2000), large structures (Ahnert & Borowski, 2000), oil and gas extraction (de Sylva et al., 2000), and nuclear tests and accidents (Livingston & Povinec, 2000; Kumato et al., 2015).

Groups of pollutants mentioned in the literature are: heavy metals (de Sylva et al., 2000; Loseto et al., 2015), pesticides (Ali et al., 2014), drugs and hormones (de Sylva et al., 2000), persistent organic pollutants (POPs) like PCB (Strain & Macdonald, 2002), hydrocarbons (Strain & Macdonald, 2002), radionuclides (Livingston & Povinec, 2000), endocrine disruptors (Mearns et al., 2013), flame retardants (Mearns et al., 2013), and hypersaline water (de Sylva et al., 2000). Those substances have various effects depending on the concentration and the substance itself, but generally speaking, they are toxic to ecosystems. There is also the issue of the bioaccumulation in marine fauna of heavy metals, pesticides, POPs and radionuclides. This contamination, going up the food chain, can potentially affect humans.

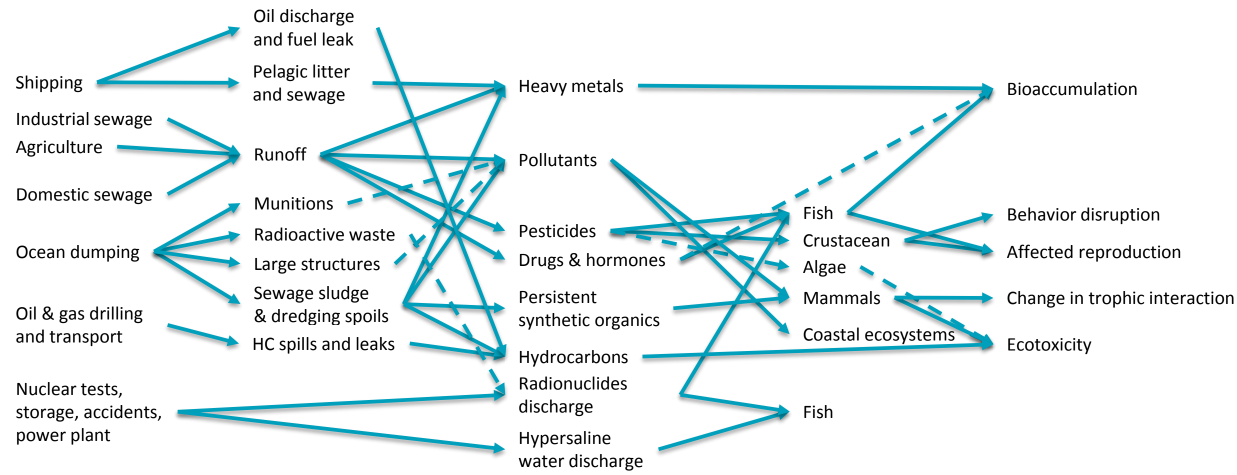

Figure 3-9: Pollutants cause-effect chain.

3.1.10 Species Invasion

The introduction of foreign species in a marine ecosystem can have dramatic effects. Often with no predators in their new environment, those invasive species can thrive and potentially out-compete native species. There are three identified transport modes for foreign species: global shipping, marine debris, and aquaculture (Bax et al., 2003; Kiessling et al. 2015; Molnar et al., 2008). In the first case, a species can adhere to the hull of a ship, be sucked in its ballast water, or stick on marine debris, and be unintentionally transported over long distances. In the second case, the establishment of foreign colonies in coastal habitats can leak and introduce the harvested species in the local ecosystem, potentially leading to cross-breeding and genetic pollution.

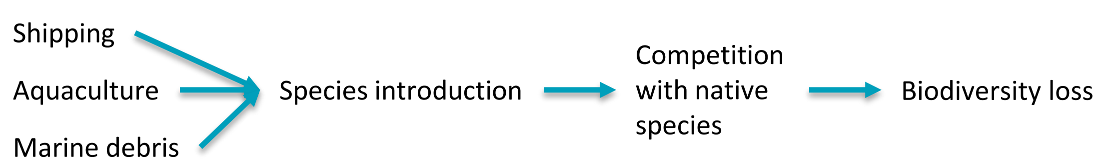

Figure 3-10: Species introduction cause-effect chain.

3.1.11 UV Radiation

Historical CFC and halocarbon emissions have had a destructive effect on the stratospheric ozone layer, which protects Earth's biosphere from hazardous UV radiation. Even though those substances have mostly been banned by the Montreal Protocol (1989), the ozone layer recovery will take several decades. Therefore, the adverse effects of increased UV radiation, e.g. increased mortality in krill populations, are still present and are a threat to marine ecosystems, especially combined with the effects of climate change (Robinson & Erickson, 2015). Effects on marine viruses, planktons, fish, the food web structure and the carbon cycle are documented in the literature (De Mora et al., 2000). According to Llabrés et al. (2012), the most sensitive taxa to increased UVB radiation are microorganisms, coral, crustaceans and fish eggs and larvae with increased mortality.

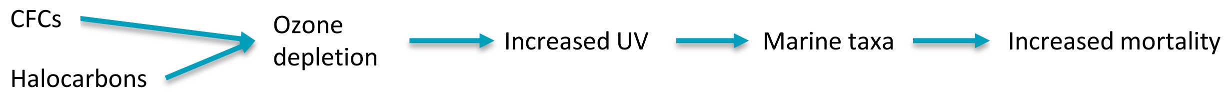

Figure 3-11: UV radiation cause-effect chain.

3.1.12 Synthesis

As could be seen from the description of the threats to ocean health, those are very diverse in their environmental mechanisms and scale, some affecting certain groups of marine species and others affecting entire ecosystems, some at a local level and others at the global level.

Marine plastic litter has the potential to affect all species, through either physical or chemical mechanisms. It also has become ubiquitous, with zones showing higher densities than others.

The next section reviews the few publications that assessed the importance of ocean threats.

3.2 Importance of Ocean Threats

This section focuses on publications assessing the importance, qualitatively or quantitatively, of several ocean threats. The description of those studies is presented in the next section, showing which threats are analyzed by each publication. It is followed by the result summary of qualitative and quantitative studies, respectively.

3.2.1 Literature Overview

Out of the 15 publications found studying multiple environmental threats to oceans, two were left out as they only covered a limited number of species. The 13 remaining are shown in Table 3-1, with the ocean threats covered by each of them. It shall be noted that most of the publications did not discuss the relative importance of ocean threats (Ahnert & Borowski, 2000; Borja et al., 2013; Claudet & Fraschetti, 2010; Coll et al., 2012; Dahms, 2014; de Sylva et al., 2000; Sheppard, 2001; Woods et al., 2016). The ones who did are presented in the following sections.

In Table 3-1, orange cells represent the dominant threats according to the publications – light orange represents publications based on a qualitative assessment, and dark orange represent publications based on a quantitative assessment. The publications are described in sections 3.2.2 and 3.2.3.

Table 3-1: Literature assessing several ocean threats.[5]

	Ahnert & Borowski (2000)	Borja et al. (2013)	Claudet & Fraschetti (2010)	Coll et al. (2012)	Dahms (2014)	de Sylva et al. (2000)	Halpern et al. (2008)[6]	Hennig (2010)	Micheli et al. (2013)[7]	Sheppard (2001)	Steffen et al. (2015)	Strain & Macdonald (2002)	Woods et al. (2016)[8]
Acidification				X			x		x		x		x
Climate change				X	x		x		x	X		x	x
Diseases			X							X		x	
Eutrophication		x	X	X		x	x		x		x	x	x
Marine litter		x			x				x[9]			x	
Noise		x		X			x		x			x	
Overfishing	x	x	X	X		x	x	x	x	X		x	x
Physical habitat destruction	x	x	x	X		x	x		x	X		x	x
Pollutants	x	x	x	X		x	x	x	x			x	
Species invasion		x	x	X	x		x		x			x	x
UV				X		x	x		x			x	

3.2.2 Qualitative Study

The paper from Strain and Macdonald (2002) discusses how to monitor ocean health in order to protect it. It considers the Canadian context, the country with the longest coastline. It describes the interactions between human activities and marine ecosystems. The authors listed 21 ocean health threats: most of them are human activities or industries (e.g. fishing), the rest are pollutants (e.g. paints or nutrients) or environmental consequences (e.g. climate change). For each, they qualified the severity (high, low or negligible) and scale (widespread or local) for the Atlantic, Pacific, and Arctic oceans[10], which allows to identify the most severe and widespread threats. Non-point source pollutants (including all contaminant sources not included in another item of the list such as organic compounds, PAHs, other synthetic

[5] Orange cells are the dominant threats according to the respective publications described in sections 3.2.2 (qualitative assessment in light-orange) and 3.2.3 (quantitative assessment in dark-orange).
[6] Global results
[7] Combined results for the Mediterranean and Black Seas.
[8] Based on the Millennium Ecosystem Assessment (2005) and Costello et al. (2010)
[9] Indirectly assessed by the coastal population density and the commercial shipping environmental drivers.
[10] Threats are also ranked for the Great Lakes, but this ranking is disregarded, the present study only covering oceans.

organic chemicals, trace metals, and plastics) and hydroelectric developments and other freshwater diversions (including habitat destruction, mercury contamination, disruption of nutrient supplies and freshwater input cycle) are the two threats ranked with high severity and widespread scale for the three water bodies. They are followed by municipal and industrial discharges, the pulp and paper industry, coastal engineering projects, spills of oil and other chemicals, and fishing, all ranked with high severity and widespread scale for two water bodies.

While the large number of ocean threats assessed by this publication is of interest, the ranking methodology is not described. Moreover, the assessment is qualified as tentative by the authors and lacks data in many cases. This raises questions about the robustness of results. While non-point or diffuse source pollutants are explicitly mentioned as an ocean threat in many other publications (Ahnert & Borowski, 2000; Borja et al., 2013; Halpern et al., 2008; de Sylva et al., 2000), this is not the case for hydroelectric production. According to Syvitski et al. (2005), humans do influence river sediment fluxes to oceans by constructing hydroelectric dams, affecting coastal erosion. However, the authors consider this as a threat to human habitat, rather than to oceans. Concerning mercury contamination from hydroelectric reservoirs, it is a known environmental issue for the freshwater biota, which can affect human health through fish consumption. However, no publications could be found about the importance of this source of mercury to the oceans. Therefore, the high severity and widespread scale of hydroelectric development in Strain and Macdonald (2002) is not considered as a robust result.

Two other publications are of interest concerning the qualitative assessment of the importance of ocean threats. Steffen et al. (2009) discuss planetary boundaries. The authors present nine such boundaries, including two directly related to oceans: ocean acidification and biochemical flows: nitrogen and phosphorus. Their importance compared to other ocean threats is not qualified. As seen on Figure 3-12 from the publication, both nitrogen and phosphorus cycles perturbation by nutrient runoff have crossed the planetary boundary into the high-risk zone, making them a more important issue than ocean acidification according to the authors. Other planetary boundaries are related to oceans, but not exclusively: climate change, chemical pollution (novel entities in Figure 3-12), stratospheric ozone depletion and biodiversity loss (biosphere integrity in Figure 3-12).

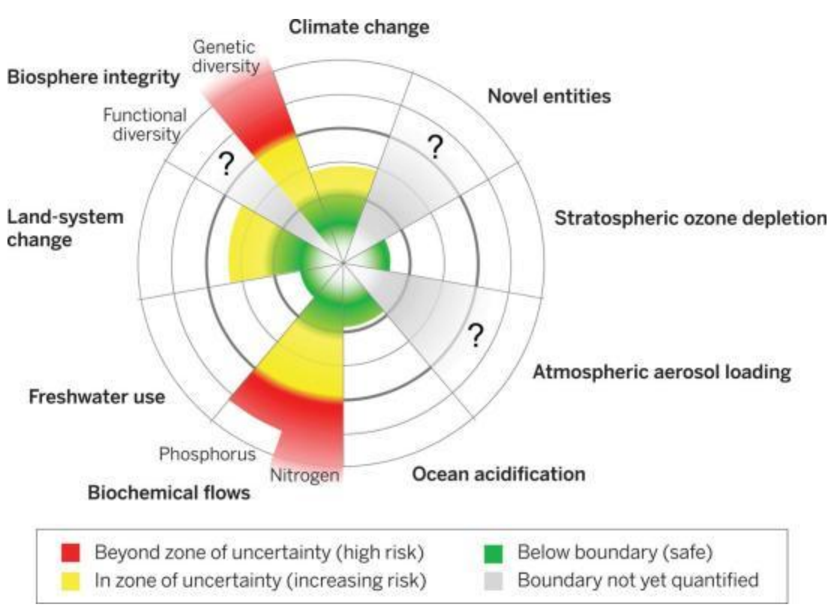

Figure 3-12: Status of planetary boundaries from Steffen et al. (2015).

In Hennig (2016), a mapping of the oceans affected by marine pollution (in general) and overfishing is done in order to demonstrate the extensive influence humans have on marine ecosystems. Those two threats are qualified as "central issues that contribute significantly to the destruction of marine ecosystems".

The qualitative assessments are summarized in Table 3-1 with the light-orange cells corresponding to the threats qualified as important by the three publications. The equivalence between the threat classification of Strain & Macdonald (2002) and the one of this report is the following: non-point source pollutants (except plastics), municipal and industrial discharges, the pulp and paper industry, hydroelectric developments and other freshwater diversions (mercury contamination), and spills of oil and other chemicals are classified as "Pollutants" in Table 3-1, coastal engineering projects, spills of oil and other chemicals (bis), and fishing activities (trawling) as "Physical habitat destruction", and non-point source pollutants (plastics only) and fishing activities (ghost nets) as "Marine litter". The threat from Steffen et al. (2015) "biochemical flows: nitrogen and phosphorus" is indicated as "Eutrophication". Those correspondences are shown in the next table.

Table 3-2: Classification of ocean threats

Publication	Threats identified	Corresponding category in this report
Strain & Macdonald (2002)	Non-point source pollutants (except plastics), municipal and industrial discharges, the pulp and paper industry, hydroelectric developments and other freshwater diversions (mercury contamination), and spills of oil and other chemicals	Pollutants
Strain & Macdonald (2002)	Coastal engineering projects, spills of oil and other chemicals, and fishing activities (trawling)	Physical habitat destruction
Strain & Macdonald (2002)	Non-point source pollutants (plastics only) and fishing activities (ghost nets)	Marine litter
Steffen et al (2015)	Biochemical flows: nitrogen and phosphorus	Eutrophication

3.2.3 Quantitative Studies

Very few authors have carried out a quantitative comparison of ocean threats. Halpern et al. (2008) and Micheli et al. (2013) did it based on very similar methodologies. From global data on multiple "anthropogenic impact drivers", the first study quantified impacts on 20 marine ecosystems covering all the oceans with a cell resolution of 1 km². They then calculated the ocean surface affected by each driver. Then, in order to compare the different drivers, each has been normalized, weighted with ecosystem-specific values, and summed across the ocean surface. The results are presented in Figure

3-13. It can be observed that climatic effects (acidification, UV radiation and sea temperature) are the most widespread, while the most important cumulative threats are climatic effects and fishing globally.

A similar assessment was done more recently by Micheli et al. (2013) in the context of the Mediterranean and Black Seas. They took into account 17 marine ecosystems in their assessment. Most of the methodology was taken from Halpern et al. (2008). The results are shown in Figure 3-14.

To calculate the cumulative scores, three steps were followed by Halpern et al. (2008) and Micheli et al. (2013):

1. Spatial data on anthropogenic drivers and ecosystems are gathered;
2. Data are log-transformed and normalized to the highest value per driver so to be between 0 and 1; and
3. Driver results are weighted by taking into account the presence of the assessed ecosystems in each cell and their sensitivity to the driver, which was evaluated by expert judgment, and summed over ecosystems, drivers and cells.

By comparing normalized driver results side by side, the authors assume that the normalization values correspond to a dangerous absolute level. Therefore, some scores may overestimate the actual, or absolute, threat level.

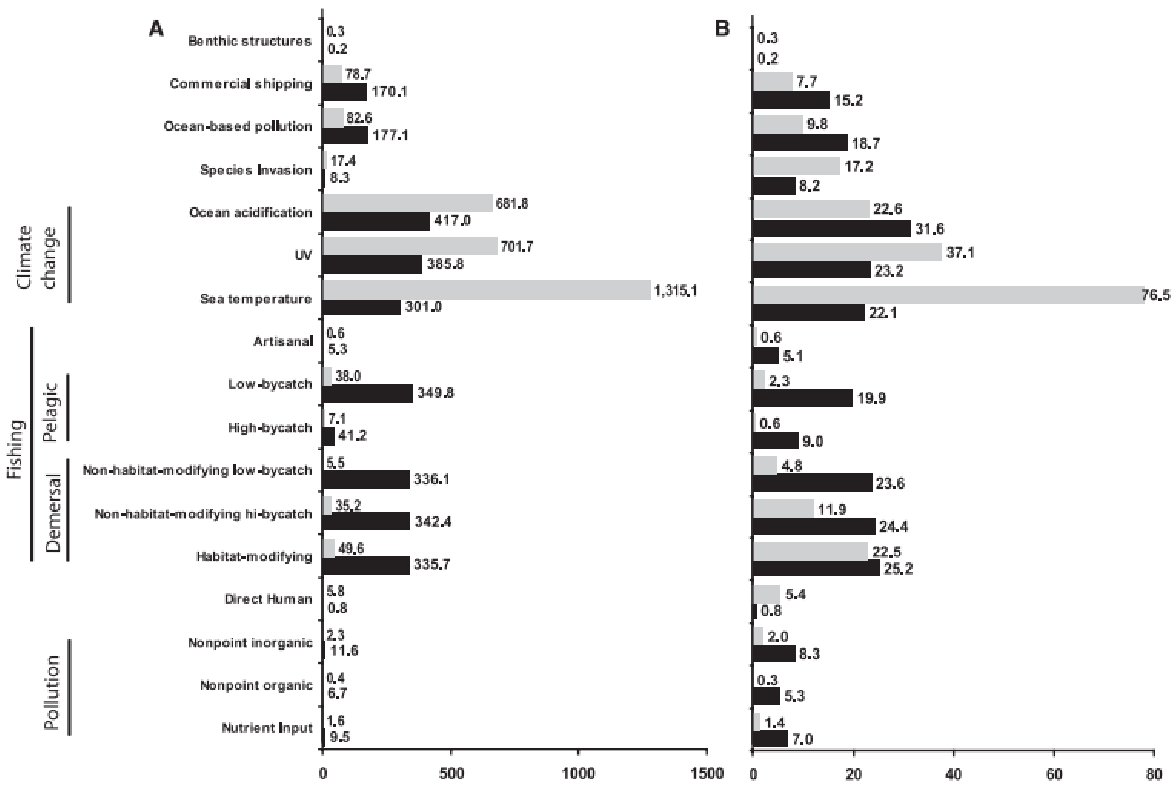

Figure 3-13: From Halpern et al. (2008). Part A shows the total area affected in km² (gray) and the summed threat scores in millions (no units, black) globally (A) and for coasts (B).

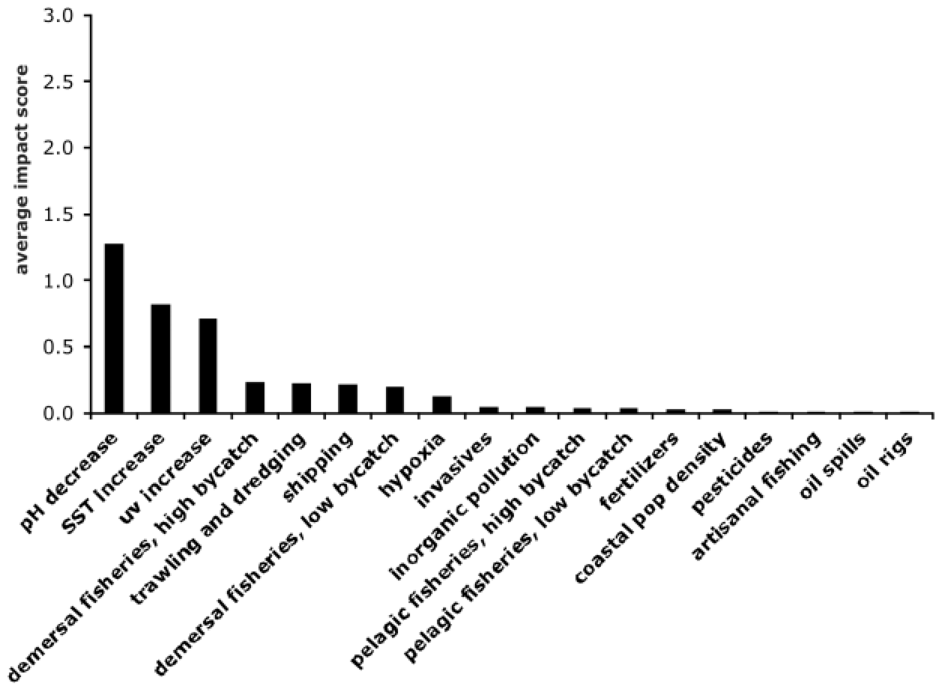

Figure 3-14: From Micheli et al. (2013). Average impact scores of drivers in the Mediterranean and the Black Seas.

3.2.4 Synthesis

Looking at the different publications qualitatively assessing multiple ocean threats, it can be observed that the importance of the threats to ocean health is not a unanimous consensus (the most important threats were highlighted in light orange in Table 4-1). Marine plastic litter was only considered by one study, Strain & Macdonald (2002), which however found it to be one of the most important threats.

Looking at the quantitative assessments (Halpern et al. (2008) and Micheli et al. (2013)), both are somewhat in agreement, differing only in the ranking of the most important threats (using the highest results shown in Figure 3-13 (black bars in section A) and Figure 3-14): all types of fishing ("Overfishing"), climate change ("UV", "Climate change", and "Acidification"), commercial shipping ("Noise"), ocean-based pollution ("Pollutants" excluding plastics), and trawling and dredging ("Physical habitat destruction"). Marine plastic litter was only considered indirectly by Micheli with the coastal population density and the commercial shipping environmental drivers, which did not obtain the highest impact results.

Finally, marine plastic litter was only covered by a few of the latest publications. This strongly hinders the assessment of its relative importance.

4 Research Needs for Integration of Marine Plastic Litter in LCA

After having put marine plastic litter into perspective with the other threats to ocean health, the second objective of this report was to identify the research needs for its integration within the LCA framework.

Woods et al. (2016) specifically identified two such research needs: plastic fate in the environment and marine plastic effects on ecosystems. Because many studies covered the former subject, a fate factor for plastic waste reaching the oceans could be calculated with strong assumptions. However, plastic fate depends on a variety of factors that are highly country-, material-, and product-specific. Therefore, more research is required to model the fate of plastics depending on where the emission occurs (environmental conditions), the composition and shape of the plastics. Moreover, plastic degradation is a key aspect of fate modeling because it affects exposure by the fauna under its different forms (e.g. macroplastics vs microplastics), which are expected to have different effects (Woods et al., 2016; Vegter et al., 2014). Studies on the fate or effect of marine plastics usually do not differentiate between plastic types, while it is reasonable to think that they will degrade or affect the environment differently. This discrimination is also useful in establishing the different pathways of plastic from source to habitat. As an example, unlike synthetic clothing particles from washing, there is no scientifically proven pathway for microplastics from cleaning products or medicines, only hypothetical ones according to Brown (2015). To address one aspect of this problem, some publications investigate more advanced plastic detection techniques based on spectroscopy, which allows to acquire more precise data on microplastic properties, such as chemical composition, particle size and concentration, than by human observation (Löder & Gerdts; 2015).

Concerning research needs on marine plastic effects on ecosystems, Woods et al. (2016) wrote that the lack of knowledge is even greater than for the plastic fate. This would especially be the case for microplastics (Lusher, 2015). Therefore, the elaboration of an effect factor that links plastic fate with impacts on ecosystems is currently not possible. Since at least the 1970s, studies have gathered information on the effect of plastic debris on animals, but to this day population-wide impact assessments are lacking (Vegter et al., 2014; Lusher, 2015). This prevents the establishment of species-response relationships, which is essential for the modeling of marine litter in LCA. According to Lusher (2015), there is a lack of data concerning microplastic fate, exposure and effect, while microplastics could potentially be more harmful than macroplastics.

The development of LCIA methods taking into account marine plastic debris could allow LCA to evaluate the environmental trade-offs of possible solutions. What could be qualified as a common belief is that biodegradable materials such as paper have fewer impacts on the environment than plastics. Past LCA studies comparing those materials, e.g. for single use carrier bags, showed preference for the latter, but did not consider marine litter (Edwards & Fry, 2011; Kimmel et al., 2014). LCA could also evaluate plastic packaging designed to increase packaging waste recovery. For example, increasing the value of plastic packaging by using more plastic may act as an incentive to recover and recycle it after use. However, using more materials means more resource use and pollution during production. LCA could evaluate the trade-off between more impacts at the production stage and less plastic litter, assuming the recovery incentive at the end of life actually works.

Being product oriented, LCA is more concerned with using the most relevant indicators for the studied product(s) than using a generic list of the most important ones at the global level. For example, the inclusion in LCA studies of plastic packaging of some ocean threat indicators is more relevant than for other materials. Marine litter is certainly the threat most directly related to packaging and may be a differentiating criterion if included. Marine eutrophication would be relevant when assessing materials made from plant feedstock due to the contribution of agricultural processes (cf. fertilizer runoffs). Other threats are not as directly linked to packaging and may not be as pivotal when comparing plastic products with alternatives.

5 Conclusions

This literature review of marine plastic litter integration in LCA first allowed to put this environmental stressor into perspective with the other main threats to ocean health. Second, it identified research needs to achieve its integration in the LCA framework.

The literature review allowed to identify and describe the impact pathways of the following main threats to ocean health: acidification, climate change, non-human diseases, marine eutrophication, marine litter, noise, overfishing, physical habitat destruction, pollutants, species introduction, and UV radiation. This showed that humans affect the oceans is very diverse ways, through diverse mechanisms and at different scales.

Only a few publications in the scientific literature compare those threats in a comprehensive way and there is no consensus as to what the most important ones are. As marine plastic litter is only covered by a few of the most recent scientific publications, its importance cannot be confidently assessed. Only one of the two reviewed studies providing a quantitative comparative assessment considered it.

Even though the inclusion of marine litter in LCA has been studied for quite some time and is getting more and more coverage in the scientific literature, the path toward this goal seems to extend still further in the future. Significant research still needs to be done to obtain robust plastic fate factors that link leakage in the environment and concentration in habitats accounting for plastic type, shape, and degradation rate. Even more work is needed to model effects on ecosystems since no effect factors have been proposed in the literature yet. Finally, microplastics are clearly one of the least understood aspects of marine litter and are the source of rising concerns in the recent scientific literature.

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Appendix A:
Bibliographic Search Parameters

Appendix A. Bibliographic Search Parameters.

Fields

Agriculture	Environmental Sciences	Oceanography
Biology	Forestry	Pharmacy, Therapeutics and Pharmacology
Botanical	Geography	Physical
Chemistry	Geology	Sciences
Ecology	Government	Statistics
Economy	Meteorology and climatology	Zoology
Engineering		

Subjects

abundance	ecosystem disturbance	ocean circulation
aerosols	ecosystems	ocean dumping
air pollution	emissions	ocean floor
analysis	environment	ocean-atmosphere system
animals	environmental aspects	oceanographiy
anthropogenic factors	environmental impact	oceans
article	environmental monitoring	oceans and seas
atlantic ocean	Erosion	pollutants
atmosphere	eutrophication	pollution
atmospheric chemistry	federal water pollution control act of 1972, section 404 permits	pollution effects
atmospheric circulation	fish	pollution monitoring
atmospheric pollution models	geosciences, multidisciplinary	precipitation
beaches	global warming	rainfall
biodiversity	greenhouse effect	research
brackish	greenhouse gases	rivers
carbon	impact	Sciences environnementales
carbon dioxide	impact monitoring plans	seawater
climate	impacts	section 404 statements
climate change	index medicus	sediment
climate models	islands	sediment pollution
climate-change	man-induced effects	sediments
climates	marine	simulation
climatic changes	marine & freshwater biology	temperature
climatology	marine biology	temperature effects
coastal waters	marine environment	variability
coastal zone	marine pollution	vegetation
coastal zones	mathematical models	waste water technology / water pollution control / water management / aquatic…
coasts	meteorology	water pollutants, chemical

community composition	meteorology & atmospheric sciences	water pollution
conservation	Model	water resources
dredging	model studies	wildlife habitat
earth sciences	Models	wind
ecology	numerical simulations	zoobenthos
ecosystem disturbance	ocean	