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# Fishing plastic waste: Knowns and known unknowns

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ABSTRACT

Plastics entering the marine environment primarily originate from land-based sources, prompting significant attention on single-use plastic packaging. However, fishing plastic waste also contributes substantially to marine plastic pollution, though it is often overlooked in the literature due to the challenges in pinpointing pollution sources. This study addresses this key knowledge gap by synthesizing existing literature to explore and document the knowns and known unknowns surrounding fishing plastic waste's environmental, health, and socio-economic impacts. Through the development of a causal loop diagram, the study offers a preliminary understanding of the issue, serving as a foundation for a deeper exploration of the complexities within the fishing industry's plastic waste dynamics. Finally, the study highlights that short-sighted views and approaches are likely to lead to systemic failures. Therefore, it advocates for strategic and meaningful measures to tackle marine plastic pollution, emphasizing the critical importance of a holistic and integrated understanding of the various plastic waste streams infiltrating and polluting our oceans.

## 1. Introduction

Plastics are synthetic or semi-synthetic organic polymers made of petrochemicals that pervade our daily lives in different forms and functions because they are cheap, durable, lightweight, mouldable, and provide good insulation properties (Derraik, 2002; Thompson et al., 2009). As a by-product of oil production, the availability of petrochemicals at low prices has resulted in the mass production of plastic materials, components, and products, the majority of which (almost two-thirds) are designed for a short lifespan (OECD, 2022, chap. 2). This, in turn, has contributed to a rapid accumulation of plastic, which, coupled with the lack of an adequate waste management infrastructure, has led to plastics becoming a ubiquitous pollutant in our environment. Estimates suggest that between 1950 and 2017 only 10 % of all plastics ever made had been recycled with the rest being burnt (14 %), buried or lying in the environment (76 %) (Geyer, 2020); leading to pollution.

To date, global attention towards eliminating plastic pollution has shifted towards plastic packaging, being the most highly produced, used, and wasted plastic item that leaks from land to the ocean (Geyer et al., 2017), contributing to marine waste. Marine waste, also known as litter or debris, refers to manmade materials, components and products that have been discarded into coastal or marine environments directly or leaked from land (Barnes et al., 2009; Galgani et al., 2015). Approximately 80 % of marine plastic pollution originates from land (Li et al., 2016), which explains the significant focus on plastic packaging waste. However, fishing gear used for direct fish capture also contributes to marine pollution and can be an important source of marine plastic pollution both regionally and locally. Plastic fishing gear that is damaged, no longer functional (e.g., nets, lines, buoys), unwanted, or single-use (e.g., baits) often ends up in the ocean through accidental loss or deliberate disposal. This abandoned, lost, or otherwise discarded fishing gear (ALDFG) is considered the largest contributor to sea-based sources of marine plastic debris (UNEP, 2016).

According to Annex V of the International Convention for the Prevention of Pollution from Ships (MARPOL): "*A fishing gear is any physical device or part thereof, or combination of items that may be placed on, or in, the water, or, on the seabed with the intended purpose of capturing or controlling the subsequent capture, or harvesting of, marine, or freshwater organisms.*" (MEPC, 2011). This definition, along with others from the literature, typically describes fishing gear, and thereby fishing plastic waste, as the equipment used for direct fish capture (Jones, 1995; Macfadyen et al., 2009; Link et al., 2019; He et al., 2021; Watson et al., 2022). However, this often excludes ancillary items like insulating polystyrene containers, ice bags used for preservation, and plastic carrier bags (MEPC, 2011; He et al., 2021; UNEP, 2016; ICES, 2022). Overlooking these ancillary items risks an incomplete understanding of

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this fishing plastic waste. Therefore, in this study, we define fishing gear, and thereby fishing plastic waste, as: "*A component, product or combination of these made from non-biodegradable synthetic polymers used, or that can be used, to capture or harvest marine or freshwater organisms, including ancillary plastic items used for their storage and preservation during fishing operations and direct sale.*"

Plastics are the dominant material in fishing gear (Watson et al., 2006). Consequently, it is not surprising that fishing gear accounts for 10 % of marine plastic waste and represents the highest proportion of macro- and mega-plastics (>50 cm) floating on the ocean's surface (Eriksen et al., 2014; Thomas et al., 2019; Morales-Caselles et al., 2021). For instance, in 2019, fishing gear was the most common category of identifiable plastic objects >5 cm (26 % by count and 8 % by mass) collected from the North Pacific Garbage Patch (Lebreton et al., 2022). Between 1999 and 2011, Pham et al. (2014) found derelict fishing gear represented the highest proportion of marine litter found in seamounts, banks, mounds, and ocean ridges in European waters, accounting for 100 % of litter present in the North and North-East Faroe-Shetland Channels, and over 85 % of litter found in the Condor Seamount, Hatton Bank and Wyville-Thomson Ridge. Furthermore, 52 % of all plastics found in the Great Pacific Garbage Patch originate from fishing activities (plastic lines, ropes and fishing nets), with fishing nets forming 86 % of the 42 k tonnes of mega-plastics (>50 cm) present (Lebreton et al., 2018). Given these figures, the true amount of fishing plastic waste from fishing is likely underestimated, as "fishing gear" only refers to fishing nets and lines. This points to key challenges in definitively attributing plastic debris items to fishing activities. Moreover, existing studies investigating the impacts of plastic fishing lines, nets and ropes often overlook the impacts caused by other fishing equipment, such as polystyrene storage boxes and plastic bags used for preserving fishing stock.

In addition, the type of fishing activities could exacerbate the problem. In 2021, 20 million people engaged in subsistence fishing, and nearly 30 million worked in capture fisheries – with 90 % of these individuals based in low- and lower-middle-income countries (FAO, 2024). Additionally, there is increasing pressure from recreational fishing in these regions, as fishery-based tourism provides a new source of income for communities (Uddin et al., 2021; Zhao et al., 2022). While participation rates are poorly defined in these areas, it is estimated that at least 220 million people engage in recreational fishing globally (Arlinghaus et al., 2019). The intensified fishing in these regions may pose a heightened risk at the local level for these communities. This was demonstrated by Daniel et al. (2020) on the beaches of the Kerala coast of India, where they found four times more fishing plastic waste on high-fishing intensity beaches compared to others. In a more recent study of 25 beaches, fishing gear was the most abundant debris item (54 %) (Daniel and Thomas, 2023). Fishing-related plastic waste also dominated in the northern South China Sea (15.3 %), residential sites of Puerto Princesa, Palawan Island in the Philippines (25 %), and the beaches of Nha Trang, Viet Nam (at least 62 % of the total by weight) (Garcés-Ordóñez et al., 2020; Fruergaard et al., 2023; Liu et al., 2023).

Fishing plastic waste has numerous physical and physiological impacts on marine biota and coastal environments (Dau et al., 2009; Macfadyen et al., 2009; Watson et al., 2022). However, there is limited recent literature on the socioeconomic impacts on coastal communities globally, especially in the Global South, where these communities rely directly on the marine environment for essential services and are therefore most vulnerable to such changes (Jones, 1995; Macfadyen et al., 2009; Do and Armstrong, 2023). This issue is often exacerbated in these regions due to improper solid waste management systems (Arifin et al., 2023; Daniel and Thomas, 2023). The lack of evidence on the quantity and impacts of fishing plastic waste on the environment and the well-being of coastal communities highlights a significant knowledge gap. This gap hinders our understanding of the plastics value chain, creating a critical blind spot in efforts to end plastic pollution. Failing to take a systems-based approach to uncover these implications risks further exacerbating this problem.

In the realm of global environmental action, the United Nations Environment Programme's (UNEP) establishment of the Intergovernmental Negotiating Committee (INC), has taken a significant step by drafting a legally binding Treaty to address the entire lifecycle of plastics, demonstrating a commitment to combat plastic pollution on a global scale by 2024. Their latest report, entitled 'Turning off the Tap', underlines the importance of adopting a systems-based approach that seeks to address the root causes rather than just addressing the symptoms of plastic pollution (UNEP, 2023). While there have been numerous calls for a systems-based approach to tackling plastic pollution, particularly in the context of plastic packaging (Phelan et al., 2020; Cowan et al., 2021; Iacovidou et al., 2021; Courtene-Jones et al., 2022; Tjarks, 2022), such an approach is yet to be applied comprehensively to fishing plastic waste.

Focusing solely on plastic packaging could prove insufficient in tackling marine plastic pollution. While, targeting land-based sources of plastic pollution is of pivotal importance, it is equally important to recognise that both land and sea-based sources play significant roles in marine plastic pollution. Ignoring either of these sources would only address half of the problem, thereby allowing it to persist. Simply eliminating plastics from land-based sources or fishing activities will not suffice. This underscores the significance of a holistic, integrated approach that comprehensively addresses the entire system within which marine plastic pollution occurs. It's not about prioritising one source over the other; rather, both sources need to be addressed with equal emphasis.

To this end, expanding our focus to include fishing plastic waste, including ancillary plastic fishing gear, is imperative in curbing the marine plastic pollution problem. Achieving this requires a comprehensive understanding of the flows and multidimensional impacts of fishing plastics, their disposal, and their contribution to marine plastic pollution. Such an understanding is essential for devising effective action plans and locally suitable solution to address this problem. Problem formulation is a prerequisite for evidence-based methods, such as, systematic evidence maps. Considering the complex interactions between human and natural systems, simple problem statements, such as Population, Exposure, Comparator and Outcome (PECO) statements, may not capture all the *a priori* assumptions regarding the interrelated nature of multidimensional (i.e., environmental, social, economic, technical and political) impacts.

This communication article aims to initiate a dialogue on the necessity of broadening our focus to include fishing plastic materials, components and products, to address holistically marine plastic pollution and protect the coastal communities that rely on fishing activities for their well-being. Additionally, it seeks to transparently document the *a priori* assumptions needed to inform the development of a protocal for a systematic evidence map. To achieve this, we examine some of the knowns and known unknowns regarding the impacts of fishing plastic waste impacts on the environment, society and economy. Following this exploration, we develop a preliminary causal loop diagram (CLD) to show the interrelationships among these impacts. CLDs are a useful means for understanding and representing complex systems, as they visualise the dynamic interrelationships (cause and effect relationships) between various variables within a system, and help identify points of intervention. Finally, we summarize the main outputs of the CLD and offer recommendations for future research.

## 2. Types and wastage of fishing plastic gear

### *2.1. Variations and types of fishing plastics*

The type of fishing plastic equipment that is used in fishing activities depends on the fishing technique employed and the spatial setting. Many fishers use a combination of synthetic nets, rope, lines, poles, floats and buoys to capture and/or harvest marine organisms, as they offer greater strength and durability than their natural counterparts.

 

Nets can be enclosed to encircle and herd organisms (e.g., surrounding nets, seine nets), pulled along the ocean floor (e.g., trawl nets, dredge nets), lowered into the water (e.g., lift nets, falling nets) or organised into stationary structures that trap fish (e.g., gillnets and entangling nets and traps). Nets are generally made from woven polymer fibres (monofilament or twisted/braided), e.g., polyamide (PA)/ nylon, polyethersulfone (PES), polyethylene (PE), or occasionally ultra-high-molecular-weight polyethylene (UHMWPE) (GESAMP, 2021).

Fishing methods involving lines often utilise terminal tackle (gear attached to the end of the main fishing line) such as lures (typically made from polyvinyl chloride, PVC) to bait fish and floats to suspend the bait at a specific depth in the water. Ropes and lines are typically made from PA (monofilament extruded and twisted), polypropylene (PP), polyester, or braided lines consisting of multiple strands of UHMWPE (GESAMP, 2021; Watson et al., 2022; Pinheiro et al., 2023). Many of these methods involve the use of buoys and floats to provide buoyancy or poles for structural support. Poles are typically made from PVC and acrylonitrile butadiene styrene (ABS). Floats and buoys can also be made from these materials, as well as PE, ABS, expanded polystyrene (EPS), ethylene vinyl acetate (EVA) and polyurethane (PUR) (GESAMP, 2021).

Larger small-scale fisheries operations tend to use commercially manufactured insulated containers, typically made of materials such as fibre-reinforced plastics (FRP) – a composite made of glass fibre with polyester resin - or high-density polyethylene (HDPE) with plastic foams for insulation. One of the most commonly used types consists of double-walled HDPE with EPS or PUR foam as insulation (Shawyer and Medina Pizzali, 2003, p. 68). In some developing regions it is common practice for fishers to purchase locally made bags of ice. One example is seen in fishing communities across Indonesia, where fishers use ice packed in single-use transparent plastic LDPE bags to cool fish caught while out at sea (Hong, 2021).

These variations in the types of fishing plastics make it challenging to capture the impacts of their use and management across their lifecycle. A thorough understanding and analysis of the production, use and management of several of these components and products is needed to adequately address this waste stream. This is a rather arduous task in an already underexplored terrain in the plastics value chain.

### *2.2. The rise of ALDFG*

Global estimates suggest that 56 % of fish aggregating devices (FADs), 29 % of lines, 8.6 % of pots and traps, and 5.7 % of nets are lost annually (Richardson et al., 2019; Gilman et al., 2021), contributing to ALDFG. However, North America and Europe are geographically overrepresented in this data. ALDFG can be the direct result of numerous pressures on fishers (Macfadyen et al., 2009), including:

- enforcement pressure causing those operating illegally to abandon gear.
- operational pressure from adverse weather increasing the likelihood of gear being left or discarded.
- economic pressure from the cost of disposal onshore resulting in dumping at sea.
- spatial pressure leading to the loss or damage of gear through gear conflicts (incidents at sea involving one or more fishing vessels).

ALDFG can also arise indirectly due to the unavailability or inaccessibility of onshore waste disposal facilities (Macfadyen et al., 2009). Richardson et al. (2018) interviewed fishers from the Global South and found that the main causes of ALDFG are snagging of nets and gear conflicts. While there is limited literature on the pathways of fishing plastic waste lost into the sea, human activities are the primary contributors.

The rise of ALDFG leads to multiple impacts across environmental economic and social domains, posing significant challenges to communities worldwide. The following section aims to explore these impacts and examine some of the knowns and known unknowns regarding the effects of fishing plastic waste impacts on the environment, society and economy.

## 3. Fishing plastic waste and its multidimensional impacts: *a priori* knowns and known unknowns

To understand the environmental, economic, and social consequences of fishing plastic waste, it's crucial to gather evidence regarding the multidimensional impacts of plastic ALDFG. However, such evidence is currently scarce. The following sub-sections, along with the comprehensive Table 1, offer an outline of the existing literature evidence concerning impacts associated with plastic debris in the marine environment, categorised into knowns and known unknowns.

**Table 1**
Summary table of the identified knowns and unknowns related to fishing plastic waste impacts across environmental, health and socio-economic impacts.

| Knowns | Known unknowns |
|---|---|
| • Drivers of gear loss (as discussed in Section 2.2)<br>• Percentage of fish aggregating devices (FADs), lines, pots and traps, and nets lost annually<br>• Main materials used in primary fishing gear<br>• Materials used in some ancillary fishing gear | • Percentage or quantity of ancillary fishing gear lost annually |
| Environmental impacts | |
| • ALDFG accumulating on the seafloor damages benthic habitats<br>• Coastal plants may pierce polystyrene from fisheries, raising trampling pressure<br>• Entanglement in ALDFG can lead to organism mortality and injury<br>• Organism mortality can result from ingesting ALDFG<br>• Ingesting microplastics from ALDFG affects the growth, productivity and cell structure of phytoplankton<br>• Indirect mortality may occur due to biomagnification of toxic persistent organic pollutants | • The quantity of methane released by ALDFG in water.<br>• The impact of benthic habitat damage on supporting services.<br>• Regional contribution of microplastics from ALDFG to marine environments.<br>• The degradation rate of ALDFG into microplastics. |
| Health and socio-economic impacts | |
| • ALDFG clean-ups demand both time and financial resources from communities.<br>• Collisions between in-use gear and ALDFG lead to financial expenses for fishers to repair or replace gear.<br>• Fishers experience productivity losses when gear is damaged or lost due to collisions. | • Proportion of microplastics from fisheries consumed by commercial marine organisms.<br>• Human toxicity effects attributable to fishing plastics.<br>• Healthcare costs associated with toxic effects.<br>• Extent of colonization of microorganisms on microplastics from fishing gear.<br>• Degree to which food chains are disrupted by microplastics.<br>• Impact of food chain disruption on commercial fish stocks and nutrition.<br>• Amount of productive fishing time lost when gear becomes unavailable due to damage or loss from collision with ALDFG.<br>• Loss of cultural services due to the presence of ALDFG.<br>• Amount of productive working time lost during clean-ups.<br>• Parties responsible for bearing the financial cost of clean-ups. |

### 3.1. Environmental impacts

The accumulation of macro plastic waste in the marine environment, including ALDFG, causes direct and indirect damage to marine flora, fauna and habitats. According to Royer et al. (2018), the increased pressure of plastics in marine ecosystems correlates with elevated carbon emissions, as plastics release methane when exposed to solar radiation in water (Royer et al., 2018). Additionally, plastics that accumulate on the seafloor, such as hook-and-line gear, derelict nets, and their fragments, physically harm benthic organism habitats by smothering them, hindering gas exchange and altering the composition of benthic biota on the seafloor (Bavestrello et al., 1997; Donohue et al., 2001; Derraik, 2002; Chiappone et al., 2005; Graham and Thompson, 2009; Watters et al., 2010). This disruption affects crucial ecosystem services provided by these habitats, including soil formation, photosynthesis, and nutrient cycling (Rife, 2018). Furthermore, dune plants have been observed to perforate EPS debris deposited in coastal environments, predominantly by fisheries, posing an indirect threat to these plants. Consequently, efforts to remove EPS during clean-up operations may inadvertently increase trampling pressure on these fragile pioneer species (Poeta et al., 2017). Moreover, floating gear can facilitate the dispersal of invasive alien species and microalgae, leading to harmful algal blooms. Gillnets, purse seine nets used in tune capture, and bottom trawls are identified as the gear types more susceptible to this phenomenon (Gilman et al., 2021).

The accumulation of macroplastic ALDFG in the marine environment also leads to organism entanglement, as highlighted by (Høiberg et al., 2022). Entanglement incidents often result in severe injury, such as mutilation and/or amputation (Yorio et al., 2014; Franco-Trecu et al., 2017), or mortality due to starvation or constriction, particularly among birds that use plastics as nesting materials, or due to ghost fishing as observed by (Gregory, 2009; Votier et al., 2011). The severity of this issue is underscored by the doubling of known species affected by entanglement in marine anthropogenic litter between 1997 and 2015, as reported by (Kühn et al., 2015). Predominantly, ALDFG associated with entanglement incidents include ropes, lines, and nets as highlighted in the studies of (Montevecchi, 1991; Page et al., 2004; Stelfox et al., 2016; Franco-Trecu et al., 2017; Jepsen and de Bruyn, 2019; Raum-Suryan and Suryan, 2022).

Accidental consumption of plastics, either directly through filter-feeding marine organisms or indirectly via secondary ingestion (animals feeding on prey that has ingested plastic) (Kühn et al., 2015), can lead to indirect mortality. This is due to partial blockage or moderate damage to the digestive tract, which, in turn, contributes to poor nutrition or dehydration (Auman et al., 1998; Gorzelany, 1998; Jovanović, 2017). Furthermore, indirect mortality can occur due to the biomagnification of toxic persistent organic pollutants leaked by plastic waste (Yuan et al., 2022), including ALDFG, upon digestion by marine organisms, such as whales, seabirds, and fish, upon ingestion (Teuten et al., 2009; Fossi et al., 2012, 2014; Rochman, 2013; Tanaka et al., 2013; Lavers et al., 2014). These pollutants, which include monomers, additives, persistent organic pollutants and metals, are either added during plastic manufacture or absorbed into plastics from the surrounding seawater (Mato et al., 2001; Rochman, 2015). For instance, a study by Rochman et al. (2013) found that 78 % of chemicals listed as priority pollutants by the US EPA were associated with marine plastic waste (Rochman et al., 2013; US EPA, 2015).

Most recently, research focus has been placed on the potential of ALDFG to contribute to the production of secondary microplastics through physical or chemical degradation processes, as demonstrated by research conducted by (Yang et al., 2021). For instance, Wright et al. (2021) estimated that nets, ropes and lines found on British beaches could potentially generate 1277 ± 431 microplastic pieces per meter of these items. The ingestion of macro- and microplastics in the marine environment by animals, often mistaken for food, can lead to direct mortality due to blockage or damage to their gastrointestinal tract, as evidenced by numerous studies (Bjorndal et al., 1994; Levy et al., 2009; Jacobsen et al., 2010; Brandão et al., 2011; Franchini et al., 2018). Furthermore, the presence of microplastics has far-reaching impacts on marine ecosystems. They affect the growth, productivity and cell structure of phytoplankton (Amaneesh et al., 2023), which play a pivotal role in global primary oxygen production, biogeochemical and nutrient cycling, and climate regulation in aquatic ecosystems (Naselli-Flores and Padisák, 2022). In addition, Desforges et al. (2015) demonstrated that microplastics originating from nylon fishing lines in the open ocean pose harm to two zooplankton species critical to the North Pacific marine food web - the neocalanoid copepods and euphausiids, through ingestion. However, the full extent of the implications for their health remains unclear.

### 3.2. Health and socio-economic impacts

Marine organisms play a crucial role in global food security and nutrition, and their consumption represents a pathway for human ingestion of microplastics. However, the extent to which microplastics from ALDFG contribute to the overall presence of microplastics in marine food remains uncertain. This proportion is likely to vary among species due to factors such as feeding mechanisms, diet, and regional differences in fishing methods. A study by James et al. (2022) shed light on this issue, revealing that polypropylene fragments from white sacs used in fish transportation were the predominant microplastic found in surface waters, sediment and the digestive tracts of commercial fish in mudbanks along the southwest coast of India. Additionally, the study highlighted higher ingestion rates among planktivorous compared to demersal species. Despite these findings, there is a high degree of uncertainty regarding the health implications, and consequently, the healthcare costs associated with the ingestion of micro- and nanoplastic particles. Studies suggest that microplastics can induce changes in the gut microbiome which can influence both physical and mental well-being (Lusher et al., 2017; Liu and You, 2023). Concerns have been raised regarding the potential physiological effects, including immunotoxicity, carcinogenicity, reproductive toxicity and neurotoxicity of micro- and nanoplastics ingestion (Li et al., 2016; Yee et al., 2021; Muringai et al., 2022; Sarma et al., 2022). Moreover, plastics such as polystyrene can generate nanoparticles that penetrate organisms through multiple routes, including the skin, respiratory tracts, and dietary intake. Once inside, these nanoparticles can interact with cellular membranes, where they can then interact with cellular structures (Kik et al., 2020).

The colonization of microplastics by microorganisms, such as bacteria, poses a significant threat to human health by facilitating the spread of potentially harmful microbes between different regions of the planet. These microorganisms can accumulate within coastal sediments, potentially leading to adverse health outcomes (Harrison et al., 2014).

Plastic waste originating from ALDFG has profound implications for depleting commercial fish and shellfish stocks (UNEP, 2016). This endangers the livelihoods of coastal communities that rely on marine ecosystems for sustenance, income, and various ecosystem services, including waste detoxification, carbon sequestration, recreational opportunities and spiritual enhancement (Worm et al., 2006; Liquete et al., 2013). The accumulation of plastic waste can disrupt fishery and aquaculture food webs, thereby affecting the quantity and quality of food available for consumption and trade (Mattsson et al., 2017; Arienzo et al., 2021; Kim et al., 2022). This disruption particularly impacts small-scale fishers who often have limited resources and operate within poorly regulated trading systems. Consequently, their livelihoods are highly vulnerable to such disruptions (Muawanah et al., 2021). In addition, fishers face risks of colliding with ALDFG during their fishing activities, leading to damage or loss of gear. This can result in lost fishing time and necessitate costly repairs or replacements, further exacerbating the financial burden on fishers (Macfadyen et al., 2009).

Furthermore, fish is an important source of protein and micronutrients for a large proportion of the human population. Food chain disruption could potentially lead to malnutrition and a consequential increase in communities' vulnerability to both infectious and non-communicable diseases, with an unknown impact. Individuals most at risk are the poor living in and around polluted coastal communities, who often have few affordable alternative food options to fish. The accumulation of plastics near the coast (Thompson et al., 2004; Critchell and Lambrechts, 2016; Su et al., 2020) affects the cultural ecosystem services received by coastal communities as well as revenue from tourism (Carson et al., 2011; Jang et al., 2014). More evidence is needed for the impacts of these services, however, this could result in loss of revenue from tourism, as well as financial and time expenditure conducting clean-ups (Carson et al., 2011; Jang et al., 2014; Gajanur and Jaafar, 2022). It is unclear how all these effects will impact individual nations' economies.

### 3.3. *Depiction of the a priori knowns and the known unknowns*

A CLD, generated using the Kumu software (Kumu, 2024), depicts the known environmental, health and socio-economic impacts outlined in the preceding sections (knowns), and hints at additional connections inferred from established knowledge or common assumptions widely accepted based on evidence from other pollution issues (known unknowns). Fig. 1 illustrates both knowns and known unknowns. It is important to note that the CLD offers a simplified portrayal of a multi-faceted system, drawing from a rapid review of existing literature and the authors' expert insights, assumptions and judgment.

In Fig. 1, solid arrows denote the connections between various causes and their effects, as supported by documented evidence (i.e., knowns). Meanwhile, dashed arrows indicate associations between causes and potential effects that can be reasonably inferred based on accepted knowledge and understanding (i.e., the known unknowns). Nodes depicted solely with dashed arrows are shaded lighter to indicate their status as identified known unknowns. CLDs facilitate the identification of reinforcing (R) or balancing (B) feedback loops. Reinforcing loops form when cause-and-effect relationships amplify impacts, whereas, balancing loops, emerge when such relationships tend to stabilise impacts (balancing effect). The compilation of illustrative reinforcing and balancing feedback loops can be found HERE.

The CLD construction began with the understanding that ALDFG in the marine environment leads to marine organism mortality through ingestion of or entanglement in macroplastics (R1 and R2). As described in Section 3.2. this imposes constraints on fishers' livelihoods due to the reduced availability of fish for consumption or trade. Consequently, fishers may find it less feasible to afford proper disposal of their gear at the end of its life, increasing the likelihood of gear being discarded in the marine environment. The degradation of ALDFG into microplastics may further increase marine organism mortality through biomagnification of leaked toxic persistent organic pollutants and potential mortality resulting from the colonization of microplastics with pathogenic microbes.

The reduced fish availability is likely to prompt governing bodies to implement stricter regulations on the illegal fishing industry to maximise the availability of quality fish stock for their populations or economic trade. However, the decline in fish stock due to illegal fishing activities may result in the disposal of fishing gear during fishing to evade arrest and subsequent penalties when inspection authorities are on the lookout (Macfadyen et al., 2009). This also implies that tighter enforcement could potentially lead to higher rates of gear dumping in this industry (R3).

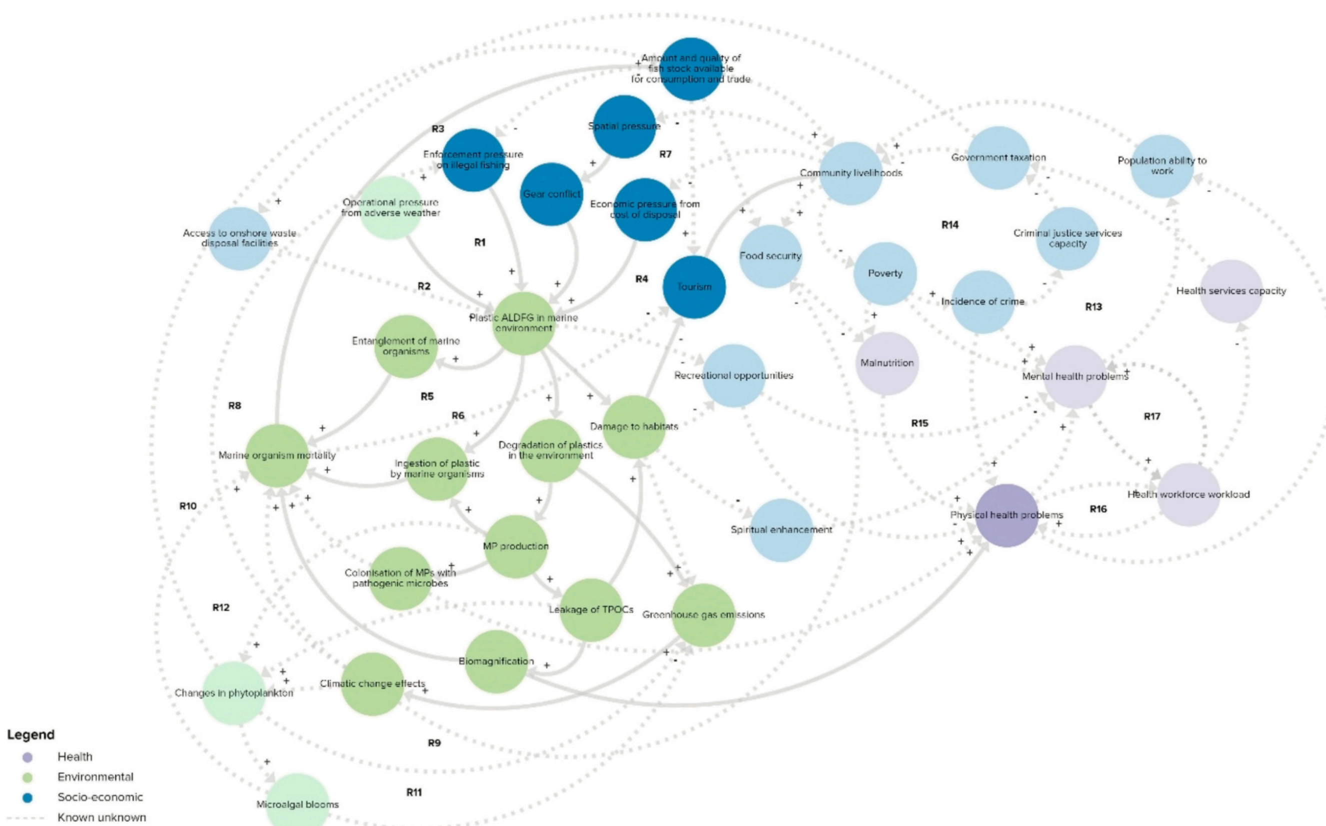


**Fig. 1.** Causal loop diagram of the known and known unknown environmental (green), health (purple) and socio-economic (blue) effects of fishing plastic pollution in the marine environment. Known-unknown causal links are joined by a dashed line. Paler nodes represent effects where all causal links are known unknowns. ALDFG = abandoned, lost, or otherwise discarded fishing gear; TPOCs = toxic persistent organic pollutants.; MP = microplastics. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article. This is found HERE.)

Plastic ALDFG in the marine environment can inflict physical damage to habitats, reducing the attractiveness of tourist destinations, and adversely affecting community income, thereby impacting their livelihoods (R4). This damage can extend to marine organisms through ingestion or entanglement in macro-plastics (R5 and R6), leading to reduced populations of species that are of interest to tourists. Moreover, recreational activities such as fishing tourism may suffer due to diminished fish stock. The resultant decline in income from fishing or tourism may drive communities to the intensification of fishing activities to compensate for their income, thereby increasing spatial pressures in fishing zones and potential conflicts over gear usage. Lost gear may inadvertently contribute to plastic ALDFG (R7). However, it remains uncertain whether fishing would indeed become the primary economic activity for these communities to offset income shortfalls.

From an environmental standpoint, the methane released during plastic degradation in the marine environment contributes to greenhouse gas (GHG) emissions, which in turn impact climate change, leading to extreme weather events. Although the extent of this contribution is uncertain, it could potentially increase accidental gear loss (R8). This sets off a reinforcing cycle where climate change, driven by increased GHG emissions, reduces the biogeochemical cycling potential of phytoplankton, thereby, emitting more GHGs (R9). This cycle is exacerbated by microplastic formation and chemical leaching, further aggravating phytoplankton's biogeochemical cycling ability and GHG emissions. Increased GHG emissions worsen climate change, contributing to changes in weather patterns, and causing more accidental gear loss (R10).

Changes in phytoplankton activity (i.e. enhanced primary production) can alter community composition, allowing specific species, like those causing microalgal blooms, to dominate (Amaneesh et al., 2023). While, microalgal blooms can remove carbon from the atmosphere, reducing GHG emissions and mitigating climate change effects (R11) (Legendre, 1990), they can also lead to marine organism mortality. This is due to the generation of large amounts of organic material that damage or clog fish gills and raise bacterial activity, reducing oxygen levels and causing hypoxia in fish (Silva et al., 2021). The resulting marine organism mortality decreases the fish stock available to trade, jeopardising the livelihoods of the fishing community and increasing the economic, spatial and enforcement pressures that contribute to more plastic ALDFG (R12).

Among the known unknowns, a potentially vicious cycle emerges for communities historically dependent on fishing and/or tourism when their primary source of income - fish stocks - disappears (R13). This decline can lead to increased poverty and may be accompanied by mental health issues, inhibiting the ability of segments of the coastal population to work, and further negatively impacting livelihoods. Another reinforcing loop (R14) arises when considering the impact on crime rates, which have been shown to rise with increasing poverty (Sugiharti et al., 2023). Increased crime rates can strain criminal justice services, increasing the demand for justice and law enforcement, which may necessitate greater taxation to fund these services. This, in turn, raises the cost of living, exacerbating the economic strain on these communities.

The rise in poverty would undoubtedly lead to more cases of malnutrition as families struggle to afford food, adversely affecting their physical health and reducing their ability to work and earn income (R15). Increased physical health problems can worsen mental health issues, resulting in a higher demand for mental health professionals. This increased workload could take a toll on the physical and mental health of the healthcare workers themselves (R16 and R17). Additionally, this strain on health services might necessitate government intervention via taxation. The extent to which fishing plastic pollution in the marine environment negatively impacts recreational opportunities and spiritual well-being is unclear. However, any losses in these services would prevent communities from receiving their associated health benefits. Furthermore, reductions in fish stocks and community livelihoods would decrease food security, leading to more cases of malnutrition and further physical health deterioration. This issue would be compounded by the potential effects of climate change on food security. All these feedback loops diminish community livelihoods, exacerbating the dumping of fishing plastic waste due to spatial and economic pressure.

These seemingly disconnected events can amplify multidimensional impacts. While the potential environmental effects are well characterised in the literature, to our knowledge, their multicausal consequences in the socio-economic domains (represented by pale nodes in Fig. 1) are less frequently discussed. To address this important knowledge gap, we are conducting a systematic evidence map to better understand the state of the evidence on this issue. Not all elements will apply equally to all coastal communities; some factors will be irrelevant in certain contexts, and some impacts will undoubtedly be missed. For example, the CLD did not account for potential impacts on the community's technical skills and knowledge related to the use and disposal of plastic fishing gear. Furthermore, it is worth noting that the social impacts associated with the loss of livelihood extend beyond health and crime to issues such as substance abuse, immigration, trafficking, prostitution etc.

This CLD is intended as a tool to identify and transparently communicate some of our a priori assumptions about the fishing plastic waste system. It is presented here to stimulate conversations with stakeholders and the research community and collaboratively identify priorities for action and further research, rather than as a positivist representation of truth. A systems-based approach aims to further explore and expose the interrelationships between the use of fishing plastics, the pollution caused by their mismanagement, and the resulting consequences for coastal communities. This approach is essential for gaining a comprehensive understanding of how these materials affect all stakeholders within the system.

## 4. Calling for a systems-based approach to tackling marine plastic pollution

The plastic treaty calls for a systems-based approach to tackle the various sources of plastic pollution, with emphasis on marine plastic pollution, yet the way this is going to be achieved remains unclear. The present study urges for an approach that encompasses both plastic packaging and fishing plastic waste to properly address the marine plastic pollution issue. This approach will utilise contextual and local knowledge of internal and external pressures on the packaging and fishing industry (such as socioeconomic and political factors), to uncover complex interconnections and feedback loops that are inherent in natural, social, economic, technical and political complex systems. It will also help to generate an understanding of the impacts at different geographical scales leading to the identification of unintended consequences, that could lead to a failure of proposed solutions. Only with such a systemic approach it is possible to gain a truly holistic understanding of the root causes and drivers of marine plastic pollution; helping to engineer sustainable transformations in the global plastics value chain.

Voicing concerns regarding a single-dimensional (one that focuses only on environmental, economic, social, or political aspects) view of the plastic packaging value chain (Iacovidou et al., 2021), is no different from looking at marine plastic pollution by focusing only on plastic packaging that leaks into the environment and oceans. While a reductionist, siloed approach may be useful in understanding elements of the root causes of a problem, it is insufficient to address complex challenges such as marine plastic pollution. It is also likely to be short-sighted, inhibiting the creation of a trajectory of action that can incentivise lasting change or worse lead to unintended consequences. Acting strategically towards ending plastic pollution globally requires mapping, understanding and analysing the problem from a system-based perspective; that recognises the complexities, realities and interconnections between different systems. Even though employing a systems-based aproach is an engaging process, it can also be intellectually challenging and time consuming. Nonetheless, a deep dive into the fishing plastic waste issue is essential for developing a new perspective on the production, use and wastage of fishing plastic materials, components and products. This in-depth analysis will also illuminate the extent of marine plastic pollution.

## 5. Conclusions

Marine plastic waste is a growing global issue, and addressing it requires understanding the interconnected systems that contribute to its prevalence. Fishing activities, whether they generate waste deliberately or accidentally, are an important source of plastic pollution. Focusing solely on plastic packaging waste will fail to address marine plastic pollution both regionally and locally. The dual-source contribution to marine plastic pollution, i.e., for land and sea based sources, is a challenge that needs to be addressed. To effectively combat this problem globally it is crucial to map, contextualise, understand and analyse its multidimensional impacts, and their interactions at different spatial scales. This comprehensive understanding can prevent short-sighted perspectives in tackling marine plastic pollution, and instead foster comprehensive solutions that encompass legislative, economic, social and environmental domains. This would ensure that we don't shift problems elsewhere, leading to systemic failures, and instead facilitate the development of strategic and meaningful measures to tackle pollution. Applying a systems-based approach, which has never been applied to marine plastic waste, can provide a framework for addressing the numerous streams of plastic waste entering the ocean around the world.

## CRediT authorship contribution statement

**Larisha Apete:** Writing – original draft, Visualization, Resources, Methodology, Investigation, Funding acquisition, Formal analysis. **Olwenn V. Martin:** Writing – review & editing, Visualization, Supervision, Resources, Methodology, Conceptualization. **Eleni Iacovidou:** Writing – review & editing, Visualization, Supervision, Resources, Project administration, Methodology, Formal analysis, Conceptualization.

## Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Larisha Apete reports financial support was provided by Natural Environment Research Council (NERC). Olwenn V. Martin reports a relationship with Food Packaging Forum that includes: board membership, consulting or advisory, and travel reimbursement. Olwenn V. Martin is one of the European Parliament's representatives on the management board of the European Chemical Agency. She is also a member of the OECD's Plastics Expert Group and sits on the Scientific Advisory Board (SAB) of the Food Packaging Forum. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

## Data availability

No data was used for the research described in the article.

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## Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.marpolbul.2024.116530.

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