Investigating the role of fishing gear on plastic pollution: The occurrence of fishing gear-related plastic ingested by Atlantic cod (*Gadus morhua*) and the fragmentation of polymer ropes

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Abstract:

Globally, the fishing industry is one key source of plastic pollution as the majority of fishing gear is made from plastic polymers and regularly used at sea. To study this relationship in an area with high fishing activity, I collected the gastrointestinal tracts (GI) of commercially caught Atlantic cod (*Gadus morhua*) on Fogo Island, Newfoundland and Labrador and dissected them for ingested plastics. The frequency of occurrence was 1.4% for 216 GI tracts. Two of the three plastic items ingested were bait bags used in cod pots and the third was a thread such as the type found in fishing rope. Following this, I conducted an experiment to test the way different polymer fishing ropes create plastic pollution during use. All polymer types emitted plastics at the same rate (total plastic particles over time), with Polypropylene and Polypropylene-Polyethylene having lasted longer during trials, allowing for more time to pollute. Various sizes and morphologies of plastics were emitted, creating different pollution profiles for each polymer type. Through my investigation of the natural environment and testing fishing gear in-use, this thesis demonstrates that fishing gear is a source of plastic pollution in both fish ingestion and through fragmentation of fishing gear during abrasion with the sea floor in Newfoundland and Labrador, Canada.

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Chapter 1: General Introduction

Since the beginning of the mass production in the 1950s, plastics have revolutionized and become ingrained in our modern society (Andrady & Neal, 2009). Longevity, durability and flexibility are the driving factors that have made plastic polymers a popular material for manufacturing products across all markets (Sigler, 2014). When plastics started to reach mainstream mass production, it was considered a ‘miracle material’ as the use of plastics had advanced various different fields on multiple fronts, from domestic spaces to industrial realms (Meikle, 1997). They provided many public health benefits from sterile surgical equipment in the medical field to reducing food waste with plastic packaging (Andrady & Neal, 2009; Opara & Mditshwa, 2013). This form of synthetic material provides incomparable design versatility that is also inexpensive compared to other alternatives (Thompson et al., 2009).

As production of plastics has exponentially increased over the past several decades, the disposal of plastics as municipal waste has become an increasingly challenge (Geyer et al., 2017). The durable properties that make plastics valuable during use, have also made it resistant to biodegradation in the environment. Additionally, there are different types of plastics used in products with various additives that make it a challenge to be separated and recycled by waste management facilities (Pivnenko et al., 2015). Most plastics end up in landfills and many plastics enter into the ocean.

Today, marine plastic pollution has changed the face of our planet, making it a core global environmental problem (UNEP, 2014). All oceans around the globe, including those once considered pristine like the Arctic, have become contaminated with plastic pollution (Provencher et al., 2010). If the consumption of plastic continues, 33 billion tonnes of plastic will exist on the planet by 2050 (Rochman et al., 2013a), with a portion of this amount entering the ocean.

While the majority of plastic pollution entering the environment is land-based, it is estimated that approximately 20% of the world's ocean plastic pollution are sea-based (recreational boating, aquaculture, offshore mining and fisheries) (Niaounakis, 2017). Modern fishing gear is one such sea-based source. It is predominantly made using plastic polymers since the transition from natural fibres in the 1960s (Brothers, 1992; Radhalekshmy & Nayar, 1973). At sea, fishing gear is exposed to extreme environmental conditions that eventually cause wear and fragmenting. Globally, it is estimated that 5.7% of all fishing nets, 8.6% of all traps, and 29% of all lines are lost at-sea every year (Richardson et al., 2019). Additionally, a third of these estimates for lost nets are attributed to being ensnared with the rough surface of the ocean floor (Richardson et al., 2019).

This is of particular concern for sustainable fisheries, as plastic pollution poses an additional threat to target and non-target species alike. Ghost-fishing, the phenomenon of catching fish by derelict fishing gear, harms fish populations and therefore fisheries (Macfadyen et al., 2009). This has led to preventative measures such as policy implementations, recovery programs and enforcement to help mitigate this phenomenon (Arthur et al., 2014). However, ingestion of plastics by commercial fish has limited preventative measures. In part, this is due to the difficulty of tracing filaments and threads once plastic debris eventually breaks down into secondary microplastics (< 5 mm) as well as the fact that many microplastics under 5mm already exist in marine ecosystems. The ubiquitous nature of broken-down plastic particles makes various species of different sizes susceptible to ingesting them. Not only can plastic pollution cause physical harm to target species, resulting in mortality, but ingesting microplastics is a potential threat for chemical contamination from toxic additives that have adsorbed onto plastic particles (Teuten et al., 2009). This poses as a potential contamination risk for food safety (Barboza et al., 2018). As fishers already face economic strain from depleting fish stock due to other environmental stressors and overfishing, plastic pollution could intensify the problem.

This thesis describes complimentary field and laboratory studies to investigate fishing gear-related pollution on the marine environment characteristic of Newfoundland and Labrador. The first study investigates the frequency of occurrence and types of plastics ingested by Atlantic cod, an important local commercial species, in an area with high fishing activity. The finding of this study, supported by the literature, is that fishing gear is a source of plastics ingested by Atlantic cod in the Fogo Island area. As such, we designed a novel study to investigate the understudied mechanics of fishing-gear related plastic pollution.

The second study looked to understand how and when abrasive wear in the benthic environment deteriorates and emits plastics from active fishing gear. I tested four commonly used polymer fishing ropes to characterize how they deteriorate and fragment from abrasive contact. I built an abrasion apparatus that simulated a rough seabed for the fishing ropes to rub against. My primary objective for this study was to understand the rate of fragmentation that occurs, the time it takes for ropes to reach failure, the total weight of plastics, proportion of plastic sizes and the type of plastic particles emitting off across all polymer types. This characterizes how each polymer type deteriorates and emits plastics in the environment.

Co-authorship Statement:

Jacquelyn Saturno is the lead author for all chapters described in this thesis manuscript under supervision and guidance by Dr. Brett Favaro, and Dr. Max Liboiron.

Jacquelyn Saturno, Dr. Max Liboiron, Dr. Brett Favaro, Justine Ammendolia, Natasha Healey, Elise Earles, Nadia Duman, Ignace Schoot, Tristen Morris are listed as co-authors on a version of Chapter 2 that is published in the peer reviewed *Marine Pollution Bulletin* (DOI: https://doi.org/10.1016/j.marpolbul.2020.110993). Author contributions for this chapter are as follows. I, Jacquelyn Saturno, secured funding, conceived and designed the experiment, performed the experiment, analyzed the data, wrote the manuscript, prepared figures and tables, and reviewed drafts of the manuscript. Dr. Brett Favaro and Dr. Max Liboiron conceived the experiment, contributed resources and funding, supervised the experiment, and provided guidance throughout experiment and analysis, and reviewed drafts for manuscript. Justine Ammendolia assisted with field and lab work. Natasha Healey, Elise Earles, Nadia Duman, Ignace Schoot, and Tristen Morris assisted with lab work.

Jacquelyn Saturno, Dr. Brett Favaro, Dr. Max Liboiron, George Legge and Ryan Doody have contributed in the completion of this research for Chapter 3. Author contributions for this chapter are as follows. I, Jacquelyn Saturno, secured funding, conceived and designed the experiment, performed the experiment, analyzed the data, wrote the manuscript, prepared figures and tables, and reviewed drafts of the manuscript. Dr. Brett Favaro and Dr. Max Liboiron helped conceive the experiment, contributed resources and funding, supervised the experiment, and provided guidance throughout experiment and analysis, and reviewed and edited drafts of the manuscript. George Legge and Ryan Doody provided technical support and consultation for the experimental design and setup.

Chapter 2: Occurrence of fishing gear-related plastics ingested by Atlantic cod (*Gadus morhua*) destined for human consumption (Fogo Island, Newfoundland and Labrador)

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2.1 Abstract

In the province of Newfoundland and Labrador, fishing is a core occupation and also a source of marine plastic pollution. To look at this relationship, I examined 216 gastrointestinal tracts of Atlantic cod (*Gadus morhua*) caught by commercial fishers at Fogo Island, Newfoundland and Labrador, Canada. I found three tracts contained plastic for a frequency of occurrence of 1.4%. While this result is consistent with other cod sampled in the province, this study found two gastrointestinal tracts contained intact bait bags, used in commercial pots, and the third tract contained a polypropylene thread, likely originating from fishing rope. Our findings demonstrate the frequency of plastic ingestion in this region is low, but fishing-gear related plastics represent a potential key source of marine plastics in the region that should be addressed.

2.2 Introduction

The exponential growth of plastic production has made the use of plastics pervasive in the consumer marketplace (Geyer et al., 2017). This growth includes the fishing industry, which has mainly shifted from using gear made from natural fibres to those built from synthetic polymers, since the 1960s (Brothers, 1992; Radhalekshmy & Nayar, 1973). The uptake of plastic polymers in fishing gear has been attributed to its durability and affordability (Brothers, 1992). In some places, like on Fogo Island, in the Canadian province of Newfoundland and Labrador, plastic gear such as nylon and monofilament gillnets were promoted through government subsidies to encourage fishers to diversify their gear in response to fishery declines (McCay, 1978). Currently, fishing gear of all kinds, such as netting, long lines, pots, seines, and trawls, are made from plastics of varying polymer types.

The long-lasting nature of synthetic fibres in fishing gear makes the gear cheaper and longer-lasting but has also imposed ecological costs on marine species (i.e. seabirds, marine mammals, invertebrates, fish, etc.) (Gregory, 2009; Laist, 1997). Both entanglement and ingestion can leave the affected individual with lesions and lacerations (Gregory, 1991). Ingestion can also result in internal blockage resulting in death of the individual, particularly when plastic items are large (Derraik, 2002; Laist, 1997). Ingested microplastics can cause negative nutritional, reproductive, or toxicological effects (Rochman et al., 2013a; Sussarellu et al., 2016; Welden & Cowie, 2016).

This is a concern for seafood consumers as previous research has identified plastics in fish and shellfish from markets, cultured from farms, and obtained through sustenance commercial fishing, all of which are destined for human consumption (Liboiron et al., 2016, 2019; Rochman et al., 2015; Van Cauwenberghe & Janssen, 2014). Relatively little is known about the fate of plastic pollution through food webs and the effects on biota as a whole (Provencher et al., 2018). Researchers, such as Rochman et al., (2015), have recommended that risk assessment for seafood safety also evaluate for plastic contamination. Additionally, preventing further ecological impacts and the associated risks from seafood contamination is most effective when efforts are focused on addressing plastic pollution at the source (FAO, 2019; GESAMP, 2019).

In Newfoundland and Labrador, marine fisheries collectively are valued at $1.3 billion and play an important cultural and socioeconomic role in the province (NL Fisheries and Land Resources, 2018). This industry is under perennial stress due to depletion of marine stocks, making conservation and stock recovery an economic priority in the region (Baum & Fuller, 2016). Therefore, any contaminant that threatens either recovery of stocks or the real or perceived value of the product is a potential threat to the industry.

An increasing number of studies in the province have found that some fish consumed as food ingest plastics, such as Atlantic cod (*Gadus morhua*) (Liboiron et al 2016, 2019). On Fogo Island, a commercial fishing region located off the northeast coast of Newfoundland, it was found that 60.5% of plastic debris collected during beach surveys was related to fishing gear (McWilliams et al., 2018). Therefore, there is a possible link between the plastics used in fishing gear and plastics that are consumed by commercially important species.

In this study, I examined the contents of gastrointestinal (GI) tracts of Atlantic cod caught in the Fogo Island Northern cod stewardship fishery (Fig. 2.1). Fogo Island is of particular interest because the fishery is economically critical to the island and has contributed to the ability of residents to avoid resettlement (Corey et al., 2014). In addition, they are employing ongoing innovations in fishing gear, including the adoption of cod pots as a potential replacement for gillnets for both economic and conservation reasons (Walsh et al., 2005).

This study has two main objectives: 1) Determine the frequency of occurrence (FO) of plastic ingestion for cod caught commercially in the Fogo Island region, and 2) where plastic is present, attempt to identify the source of the contaminant.

2.3 Methods and Materials

I collected individual Atlantic cod off the inshore coast of Joe Batt's Arm, on Fogo Island, in the province of Newfoundland and Labrador (49°45′ 52.52″ N, 54° 12′44.96″ W)(Fig. 2.1). On three separate days, I joined fishers from the Fogo Island Co-op as they fished at sea. Each trip I collected 75 GI tracts from Atlantic cod captured during commercial fishing. The cod were caught using baited pots, a stationary, cage-like fishing trap that use bait in black plastic bait bags to attract fish (Meintzer et al., 2018). Before extracting their GI tracts, I recorded the fork length of each cod to the nearest cm. I then removed the entire GI tract, placed them into individually labelled bags and froze the contents at -20°C when I returned to land. In total, I collected 225 GI tracts. Nine GI tracts were excluded because they were damaged and potentially exposed to contamination or lost contents. Therefore, I retained 216 GI tracts in our analysis, all of which had associated fork length measurements, and 199 associated sex (see Appx 2.3 for comparison of sample size to similar studies in the field). All sampling followed protocols outlined by the Animal Care Services at Memorial University.

I conducted the collections in late August of 2017 during the Northern cod stewardship/by-catch fishery. Towards the end of August, Atlantic cod are primarily feeding in the benthic environment as capelin, one of their main food sources, will have finished spawning and migrated offshore (Fisheries and Oceans Canada, 2019). With the cod unselectively feeding on the benthic environment, they are at risk of ingesting plastics (Melvin, 2017). Especially fishing gear-related plastics, a large contributor to pollution of the seafloor (Corcoran, 2015).

During laboratory analysis I undertook precautions to reduce the potential of contaminating samples from the laboratory environment (Davison & Asch, 2011; Foekema et al., 2013). Prior to GI tract dissections, I cleaned all tools with tap water and Kimwipes™, including the microscope lens and plate, petri dishes, and sieves. I wore nitrile gloves and a cotton lab coat and tied my hair back. To prevent cross-contamination between samples, I meticulously cleaned all tools following every dissection. As a control, I placed an open petri dish with sticky tape next to our workspace during dissections to collect airborne plastic microfibres. This enabled us to measure a baseline of potential airborne contamination for each sample. The open petri dish was then closed, dated and replaced with a new petri dish after each dissection day. I visually inspected this control dish as the study proceeded to compare any microfibres with those in the control dish, eliminating them from the study if they were identical. Additionally, between samples I inspected and cleaned our nitrile gloves and dissection tools of any airborne microfibres that may have stuck on during the examination process.

I removed the GI tracts from the freezer, where they were frozen at -20°C, and thawed them for two hours at room temperature. A double-sieve method was used by stacking a no. 4 sieve (4.75

mm mesh size) on top of a no. 18 sieve (1 mm mesh size). I used the lower threshold of 1 mm, as anything smaller than 1 mm were not reliably identifiable with the naked eye (Song et al., 2015). Plastics and contamination smaller than 1 mm were not included in this study.

I placed one defrosted GI tract at a time on top of the no. 4 sieve and washed the exterior with tap water. I then made an incision into the tract starting from the esophagus, then moving to the stomach, the intestines and to the anal canal to separate the larger biological content and identify any plastics. I used a wash bottle to rinse GI tract contents onto the sieves, and then visually inspected the stomach lining for embedded plastics. I recorded the sex of all but 17 individuals, and whether GI tracts contained organic material, sediment, or were empty. Any particles that were suspected to be anthropogenic, including but not limited to plastics, were removed and transferred to a petri dish and dried for further analysis. The suspected particles were examined using a dissecting microscope (Olympus SZ61, model SZ2-ILST, with a magnification range of 0.5 – 12 X).

The potential plastics were characterized based on morphology using the following categories: thread, thick filaments that are large enough to see eroded or frayed edges clearly, often with multiple twisted strands visible (such as those found in fishing gear); microfibre, thinner compared to threads and usually without eroded edges, often kinked and sometimes in tangled clusters (such as "lint" originating from clothes); fragment, subround/angular particles with an irregular shapes that have varying heights, widths, and lengths; pellets, industrial pre-production round plastics that look similar to beads, usually a single colour; foam, plastics that have air pockets and bounce back to the touch; film: thin, flexible plastics with height and length but minimal width (such as plastic bags).

To confirm visual inspection, particles suspected to be plastic underwent further analysis through Raman micro-spectrometry, a widely used technique to identify microplastics by determining the polymer characterization of the suspected sample (Goh et al., 2017; Lenz et al., 2015). Samples were cleaned using 95% ethanol to remove organic matter prior to running the spectra analysis. The Raman micro-spectrometer (Renishaw InVia with an 830 nm wavelength) was calibrated using a silica wafer with a known reference peak of 520 cm^{-1}. Following calibration, potential plastic samples were analyzed using the microscope's 20x objective lens. To reduce the level of fluorescence and prevent the sample from burning, the laser power did not exceed 5%. Renishaw's Windows®-based Raman Environment (WiRE™) 3.4 software package was used for instrument control and data acquisition. Each spectrum produced was matched with a reference spectra from SciFinder.

2.4 Results

Of the 216 cod examined, body size ranged from 50 to 105 cm (mean = 73 ± 0.78 cm SE) (Appx 2.1), 103 were male, 96 were female, and the sex of 17 individuals could not be identified. Out of the GI tracts that were examined, 57 (26.4%) were empty. The remainder 159 (73.6%) contained stomach contents (Appx 2.2A).

The 159 GI tracts that contained stomach contents had the following prey items present: arthropods (60%), echinoderms (32%), molluscs (4.4%), and seaweed (17.6%) (Appx 2.2B).

Other ingested content that is characteristic of the benthic environment included sediment (12.6%). In addition to benthic-related content, Atlantic cod (10.7 %) and unidentifiable fish species (3.1 %) were found as well as capelin and squid, which are used in commercial cod pots (62.9%). Since the cod were benthically feeding during the collection period, the capelin and squid (both pelagic species) were concluded to be bait (Black et al., 1987; Fisheries and Oceans Canada, 2019). Additionally, capelin had also migrated offshore at the end of summer (Fisheries and Oceans Canada, 2019).

In total, three GI tracts contained plastics. In two cases, the tract contained fully intact bait bags used in the commercial fishery to hold bait capelin and squid in cod pots. These bags were macroplastics (> 25 mm)(GESAMP, 2019) (23.8 cm bag in a 70 cm cod; 25.0 cm bag in a 96 cm cod) (Fig. 2.2A and B). The bait bags found within the stomachs still contained capelin. The third plastic was a weathered piece of thread that appears to have fragmented off of a larger type of plastic, likely a rope given the structure and polymer type (Fig. 2.2D). I found this macroplastic thread (length 39 mm) in the GI tract of a 69 cm cod. This cod had also consumed seaweed (i.e. green kelp and red algae) and echinoderms (i.e. brittle stars), indicating that it had been feeding on the sea bottom. Besides the ingested plastics, no other form of anthropogenic debris was identified.

The produced spectra for the thread was compared with reference polymer spectras confirming the thread to be polypropylene (Ahmed et al., 2010; Clunies-Ross et al., 2016) (Appx 2.4). Clippings from the bait bags were analyzed to determine polymer type. The produced spectra for the black mesh of both bait bags were confirmed to be polyethylene from published spectra

(Clunies-Ross et al., 2016; Tóth et al., 2006)(Appx 2.4). Orange draw string was also analyzed but produced too much fluorescence in the produced spectra to get a proper reading to confirm polymer type. The blue band holding the bottom of the bait bag together was not analyzed to determine polymer type.

2.5 Discussion

Of the 216 fish examined, three (1.4%) had ingested macroplastics. This frequency of occurrence (FO) is consistent with other Atlantic cod ingestion studies in Newfoundland and Labrador (1.68% in Liboiron et al., 2019; 2.4% in Liboiron et al., 2016). Our findings are similar to other locations like Norway (3% in Bråte et al. 2016) and the Baltic Sea (1.4% in Rummel et al., 2016), but is lower than the FO recorded in the southern North Sea (13% in Foekema et al., 2013).

Of the three plastics found in this study, two were confirmed to be fishing gear-related and the third is suspected to have originated from fishing rope. The bait bags were intact and easily identifiable, and the polypropylene thread was found in an area with high fishing activity and a common polymer type used in fishing ropes (Radhalekshmy & Nayar, 1973). The thread also has characteristics (colour, polymer type, fraying) that lead us to hypothesize that it originated from fishing rope. Other ingestion studies have identified plastic threads in areas of high fishing activity that resemble fishing rope and lines (Dantas et al., 2012; Liboiron et al., 2016; Ramos et al., 2012). While the bait bags are large enough to cause gastrointestinal blockage, the thread was small enough to potentially pass through the fish's GI tract without causing internal blockage.

With the reported FO being low, the exposure concentration from consuming the associated chemicals from plastics are also expected to be low.

Atlantic cod are vulnerable to plastic ingestion because they are opportunistic feeders that exhibit non-discriminatory feeding behaviour of various prey (Reiss et al., 2005). Cultured Atlantic cod have been observed to bite loose threads in netting and create holes large enough to escape (Moe et al., 2007). The cod could have ingested the polypropylene thread by interacting with intact fishing gear or it could have ingested the thread as an already existing piece of fragmented plastic. There were holes in the ingested bait bags and over 50% of all cod stomachs contained bait (Appx 2.2B), indicating that the cod were attracted to and nibbling at the bait bags within the pots. Two individuals were successful in consuming the bait bags with the bait included.

The findings of this study will hopefully start the dialogue for fishing gear to be modified in order to pollute less plastic during fishing operations. As cod pots were introduced as a more sustainable option for fishers to use, using plastic bait bags that can be ingested by the targeted species is a concern for fishers that are catching cod using a method believed to be sustainable. From a fisheries gear standpoint, addressing plastic pollution starts with designing gear to reduce the risk of emitting plastics into the marine environment. Just as fishers around the world switched from natural to synthetic fishing gear to increase productivity and economic income (Martinussen, 2007), the fishing industry has the ability to change gear in a way that maintains the integrity of the oceans by reducing pollution.

I would like to make the following recommendations for the fishing industry: (1) preventative action is required by re-designing gear to prevent loose components such as bait bags from getting lost at-sea and; (2) remove worn and derelict fishing gear to a waste management facility in order to prevent fragmentation of large gear into microplastics and threads. Generally, I also recommend that more research is conducted to develop low-impact gear designs and truly biodegradable materials to reduce reliance on plastic polymers. These forms of preventative action will reduce the likelihood of a future plastic pollution crisis in our food fisheries.

2.6 Figures

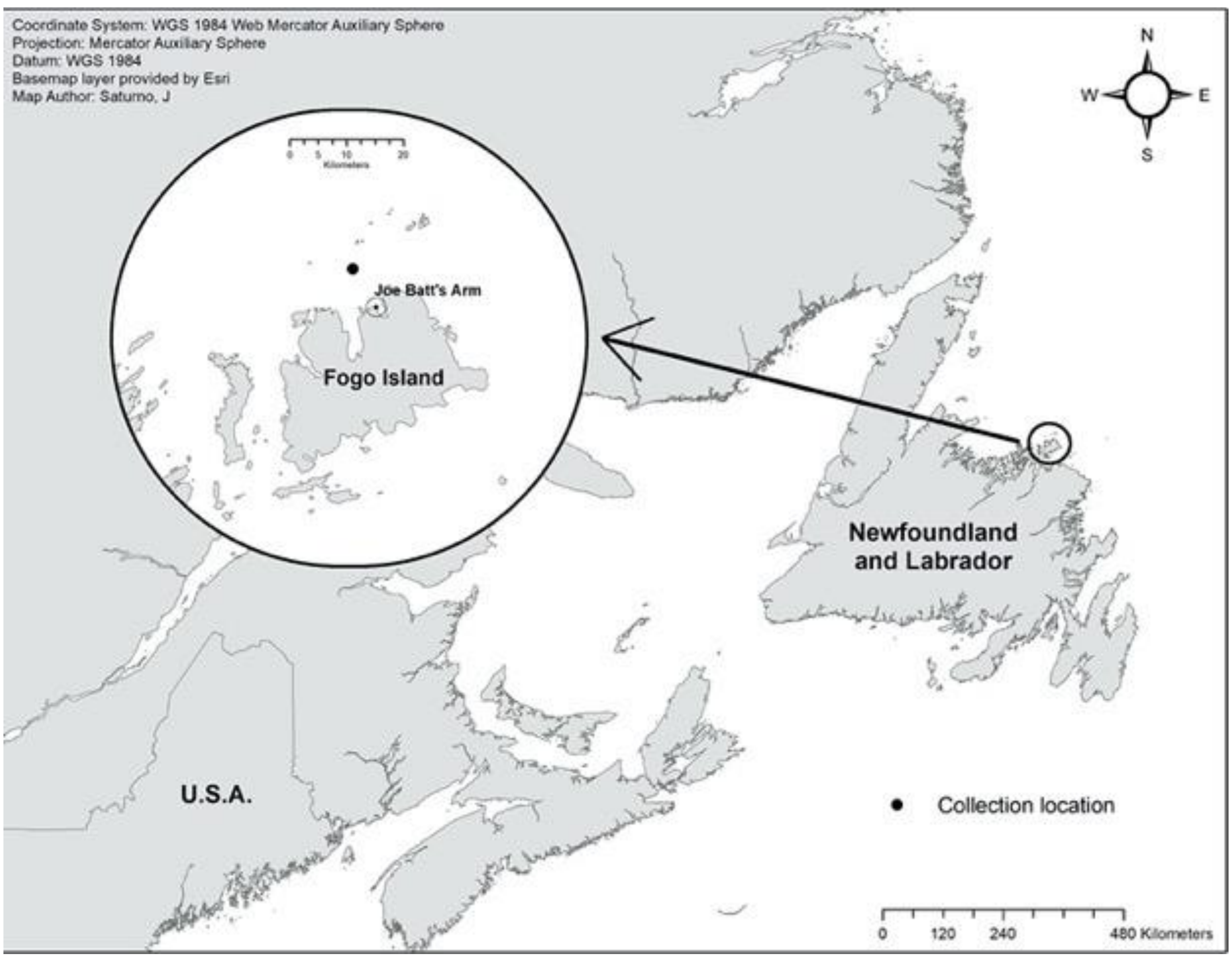


Fig. 2. 1 Collection location for Atlantic cod with commercial fishers of the shore of Joe Batt's Arm, Fogo Island, Newfoundland and Labrador.

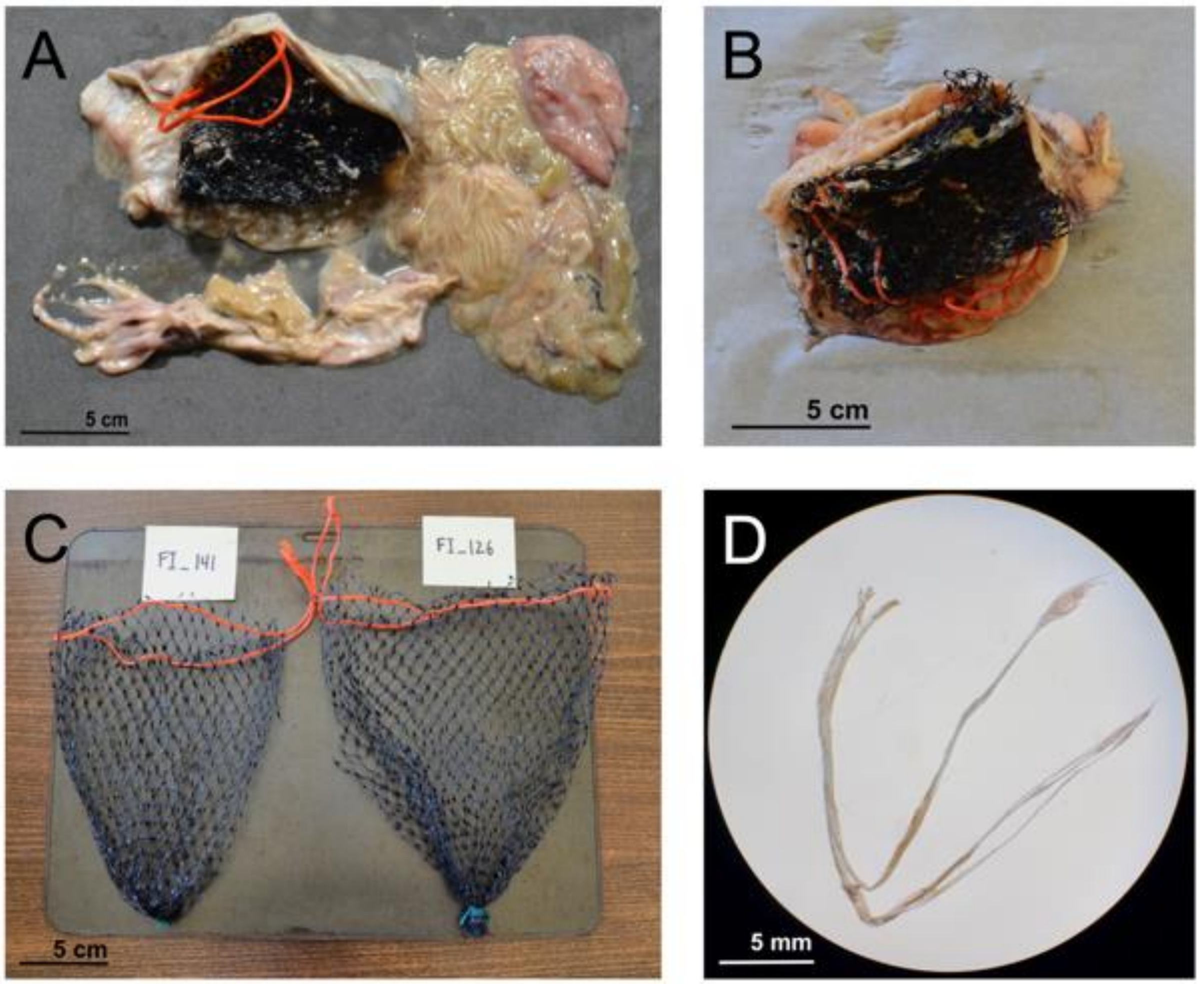


Fig. 2. 2 Photographs of plastics ingested by cod. Bait bags photographed in situ in (A) the GI tract of a 70 cm female cod and (B) the tract of a 96 cm female cod. Photograph (C) shows the two bait bags from A and B spread open on a dry surface. (D) shows the polypropylene thread 39 mm in length found in the GI tract of a 69 cm male cod.

Chapter 3: Comparison of the creation of plastic particles from abrasive environmental contact of four polymer fishing ropes

3.1 Abstract

Studies conducted in fishing communities around the world, including Newfoundland and Labrador, Canada, have identified fishing gear as a major source of plastic contamination. Yet the conditions under which fishing gear fragments plastic particles during use have not been adequately investigated. In this study, I compare four different plastic polymer ropes that are commonly used in the fishing industry (Nylon (PA), Polyethylene (PE), Polypropylene (PP), Polypropylene-Polyethylene (PP-PE) blend) to characterize their fragmentation in abrasive environments. Ropes were abraded against an artificial seabed to simulate fishing activities in the benthic environment. Trials were conducted in standard five-minute intervals that ended when ropes reached 50% diameter loss. Out of the four polymers, PP rope lasted the longest (mean = 77 minutes ± 7.6 SE), followed by PP-PE (mean = 56.5 minutes ± 4.3 SE), PA (mean = 36.5 minutes ± 3.0 SE) and PE (mean = 34 minutes ± 2.4). The rate of total plastic particles emitted over trial time was the same across all polymer types, so polymers that lasted longer during trials, like Polypropylene and Polypropylene-Polyethylene, have more opportunity to deteriorate and fragment. Polymers that lasted the shortest amount of time, like PA and PE, created fewer plastic particles to be emitted but would require that ropes be replaced more frequently. Different sizes and morphologies of plastic particles were emitted by each rope type, resulting in different plastic pollution profiles. Given that fishing gear is used in abrasive conditions in the marine environment on a frequent basis, this indicates that this is likely a prominent source of plastics debris polluting the oceans.

3.2 Introduction

Plastic pollution in the ocean is an issue of global concern. It can harm wildlife in a variety of ways, including chemical transfer (Rochman et al., 2013b), entanglement, ingestion and smothering (Gregory, 2009). Consequently, the properties that make plastics so durable, also make it difficult to readily decompose under normal circumstances (Khare & Deshmukh, 2006). However, through exposure to UV radiation, warming temperatures, and environmental mechanical forces like wind and waves (Albertsson & Karlsson, 1988; Barnes et al., 2009; Singh & Sharma, 2008), larger plastics have the capability to fragment into smaller particles, known as secondary plastics (Cole et al., 2011). Both derelict and active fishing gear are exposed to these processes and can create secondary plastics.

Commercial fishing gear is predominately made from plastics and favoured over natural fibres because of their low cost, long life-span, and durability (Brothers, 1992). Consistent use and exposure in the marine environment can wear down gear leading to unintended lost gear or gear components at sea, as well as fragmentation. Fishing gear has become a key source of plastic pollution for coastal communities adjacent to high fishing activities (Goodman et al., 2020; Walker et al., 1997). In Newfoundland and Labrador, Canada, studies have found fishing gear in the marine and coastal environment is related to cetacean entanglements, plastic ingestion by marine animals like Atlantic cod, plastic incorporation into seabird nests, and beach pollution (Benjamins et al., 2012; Bond et al., 2012; McWilliams et al., 2018; Saturno et al., 2020). Recently, fishing gear has been found to constitute an average of 37% of all shoreline marine litter (Liboiron et al., in prep). Plastic threads of various sizes that have fragmented from fishing ropes are commonly spotted during beach surveys in Newfoundland and Labrador (Melvin et al., in prep). Plastic particles have been located in various levels in the water column due to density, size and shape, making them bioavailable to diverse marine species (Choy et al., 2019).

Preventative measures aimed at reducing fishing gear loss are taken into account during the manufacturing and designing process. Fibre ropes undergo testing to meet international standards to ensure performance quality (Weller et al., 2013). This includes tensile testing to determine the rope breakage load and abrasion tests to improve wear on ropes and reduce unexpected breakage. This synthetic material has been chemically engineered and continuously improved upon to maximize efficiency and durability. However, fragmentation of gear, specifically tensioned ropes, still may occur due to repeated contact against the rough seabed (Seo et al., 1997; Welden & Cowie, 2017).

Most scientific literature on plastic fragmentation of fishing gear in the environment focuses on lost or discarded gear (Richardson et al., 2019; Welden & Cowie, 2017). Plastics emitted from fragmentation that occurs during active fishing activity has, to my knowledge, not been studied to date. As previously mentioned, current material science research tests commercial ropes for abrasion resistance prior to being put on the market (Flory et al., 2004), but do not investigate the mass of plastics that fragment and can subsequently enter the ocean. During fishing operations there is a considerable amount of strain, abrasion and friction between plastic ropes and various surfaces that the gear interacts with. Ropes can be abraded from continuously being run through hauling machines as well as with hard surfaces like fibre glass, wood and metal on fishing vessels (Grimaldo et al., 2019). Fisheries in Northern Europe like Denmark protect high-value bottom trawls from damage by attaching protective “dolly rope.” This type of polyethylene rope unravels during the dragging and acts as a barrier between the netting and the seabed. By design the intense abrasion causes the dolly rope to undergo wear and tear instead, fragmenting off polyethylene threads (Mengo, 2017; Ryberg et al., 2018). Given the high degree of abrasion that occurs during fishing, it is likely that polymer fishing gear experiences fragmentation not just when it is lost, but also when it is in active use. Understanding when and how this occurs – and which materials are most susceptible – is therefore of value for mitigating fragmentation and thus microplastic pollution during fishing activities.

In this study, I tested four plastic polymer ropes: Polypropylene (PP), Nylon (PA), Polyethylene (PE), and Polypropylene-Polyethylene (PP-PE) blend. I built an apparatus to conduct a controlled abrasion experiment in which I rubbed each type of fishing rope against a simulated rocky seafloor. I measured six factors to test how each polymer rope deteriorates in response to stress by investigating the following: 1) the amount of time taken to break down the ropes, 2) the rate of plastic emission (total plastic particles over time), 3) the total weight of plastics emitted, 4) the trend of plastic particle emissions and rope deterioration within each trial, 5) the proportion of three plastic size classes emitted and 6) characterizing the failure event of rope snapping to qualitatively assess the extent to which failure causes fragmentation.

3.3 Methods and Materials

3.3.1 Rope specifications

I tested four different types of plastic polymer ropes chosen for their common usage within the fishing industry since the transition from natural fibres (Oxvig & Jes Hansen, 2007; Radhalekshmy & Nayar, 1973). A co-polymer blend (PP-PE) was specifically selected based on its common usage in the fishing industry in NL (Pers. Comm. from Dave Kelly, Hampidjan). The polymer type ropes were as follows; Nylon (PA) and Polypropylene (PP) manufactured by DSR Corp™, Polyethylene (PE) manufactured by Cotesi™, and Polypropylene-Polyethylene blend (PP-PE) manufactured by Axiom™. The ropes all had a three-strand twisted structure, a 1.3 cm (labeled 0.5 inch) total diameter and the breaking loads according the manufactures' rope specifications were as follows: PE: 1580 kgf; PP: 3212 kgf; PA: 2682 kgf; PP-PE: 2396 kgf. All were purchased new from local marine supply stores and manufactured from suppliers overseas.

3.3.2 Experimental apparatus

I designed the experimental apparatus to simulate a rope rubbing against a rocky seafloor during fishing operations. The artificial seabed was a 7.6 x 30.5 cm (3 x 12 inches) pine wooden board onto which I embedded rocks and sediment collected from beaches of Placentia Bay, a fishing area located on the southern Avalon peninsula of the island of Newfoundland (47°6′10.8″ N, 54°11′9.24″ W). After cleaning the materials to remove potential environmental sources of plastic I embedded them onto the board using marine welding hardener and resin and filled gaps between rocks with Six10 marine epoxy. The completed artificial seabed was essentially a rectangular wooden block with rocks adhered to one side (Fig. 3.1).

The artificial seafloor was positioned with the seabed-side facing down submerged in saltwater (33 ppt, ambient temperature) in a 1200 L fibreglass aquaculture tank (Fig. 3.2). The board was mounted with two threaded rods on either end to a 90.7 kg flat metal weight (71 x 71 cm) to keep the seabed weighed down and in place. The distance between the board and the weight was 25 cm, allowing for enough room for the rope to be fed across the board (Fig. 3.2).

For each trial, the tank was filled with approximately 1/3 with static volume of artificial saltwater, just enough to cover the simulated seabed platform. Each sample rope was cut to 4.6 m in length with one end connected by shackle to a braided wire cable threaded through a pully and held taut by a weight (11.8 kg). On the other end, the rope went into the water of the tank, fed underneath the simulated seabed board against the sediment, and then exited the water and was tied to the cable wire from the electric cable hoist mounted 3 meters up to a wall beam (Fig. 3.2).

This cable hoist had the capacity to haul 200 kg (440 lb) and was controlled by a Raspberry Pi 3 Model B computer. I used a Python syntax to program a Raspberry Pi computer for the cable hoist to operate on a timer to command the cable to move up two seconds, rest for two seconds and move down for two seconds, allowing for 70 cm of rope to be abraded against the artificial seabed for a total of five minutes per interval (Appx 3.1).

3.3.3 Experimental procedure

This study consisted of a series of independent experimental trials. Each trial proceeded in standardized steps. First, I soaked each rope in artificial saltwater for a 24-hour period, allowing the ropes to be in a wet state, simulating real at-sea conditions (Backer et al. 1981). A single trial consisted of one rope being subjected to abrasion by rubbing the simulated seabed in a series of five-minute intervals. After five minutes of rubbing, the apparatus halted and I collected any plastic particles that came off the rope and measured the rope diameter before the next time interval. I had terminated the trial when the rope diameter was reduced to 50% of its original starting width, which represented a rope condition that would be unsuitable for continued use in fishing operations.

PP, PE, and PP-PE are less dense than saltwater, so their particles floated on the surface. After the completion of every five-minute interval, particles were collected using a 150 μm sieve attached to a metal extension pole. Since Nylon (PA) is denser than saltwater, I collected the particles using a net (150 μm mesh) positioned directly underneath the board to catch particles. The net had 10 small lead sinker weights (28 g each) evenly distributed to create a concave dip in the middle to better capture the PA particles (Fig. 3.3). To hold the net in place directly underneath the seabed board, I attached the corners of the net with clamps onto the tank's ledge. Floaters attached to the sides of the net prevented the net from collapsing in on itself and losing plastic particles as the net was pulled up from the tank. After removing the net, I visually inspected the tank for any potential escaped plastics. This was a rare occurrence but any visually identified plastics that had escaped the net would be collected (Fig. 3.3). Using both collection methods, the cut off size of the plastic particles collected was 150 μm. The collected plastic particles varied in size and was later separated by size class (micro 0.5 mm – 5 mm; meso 5 – 25 mm; macro >25 mm) as part of sample processing in section 3.3.4. As I was manually collecting the plastic particles, I used a finer mesh size than the 0.5 mm cut off to be thorough during the collection process. After each five-minute trial, all collected plastic particles were stored in clean labeled glass jars. The plastic particles were later dried inside cone coffee filters, with a mesh size smaller than sieves used to catch them, prior to further analysis.

In plastic pollution research, controlling for contamination is crucial to prevent any airborne plastics in the surrounding environment from mixing in with the samples. All polymer ropes used were different colours and I ensured that no plastic particles with similar colour or thread morphology were present in the test area. Based on morphology, most airborne contamination are microfibres rather than threads (Torre et al., 2016). Visual inspection was deemed sufficient to identify study plastics from contamination.

For each of the four polymer ropes, 10 trials were replicated (40 trials total). At the conclusion of each trial, I set the deteriorated ropes aside for the breaking experiment (described below). Between each experimental trial I replaced the water in the tank so as to avoid cross contamination of plastic particles from one trial to the next.

3.3.4 Processing plastics

Within this chapter, the term plastic particles will be used to refer to all plastic morphologies, including threads and fragments of various sizes, that emitted from the ropes. The total weight of dried plastic particles emitted during each five-minute interval was weighed to the nearest 0.0001 g using an analytical balance (Satorius BP-210). The plastic particles were weighed, rather than counted, given the large amount of plastic that had emitted (ranging from micro- to macroplastics) and the increased risk of losing particles from extensive handling, it was logistically unrealistic to count each individual piece. I had then separated the plastic particle samples into three standard size classes (micro 0.5 mm – 5 mm; meso 5 – 25 mm; macro >25 mm) (GESAMP, 2019) using sieves and digital calipers. I did not record the presence of microplastics smaller than 0.5 mm due to limitations of accurate visual identification (Rochman et al., 2015). To separate micro- and mesoplastics from the total sample, two sieves were stacked on top of each other, a no. 4 sieve (4.75 mm) and no. 35 (0.5 mm) respectively, with the microplastics falling onto the no. 4 sieve and the mesoplastics staying on the no. 35 sieve. Mastercraft digital calipers were used only to distinguish macroplastics from mesoplastics by measuring and separating the particles larger than 25 mm. Microplastics were too small to be measured with calipers, so the sieves were used to distinguish microplastics from mesoplastics. Samples from each trial in each size class were then weighed to the nearest 0.0001 g using the analytical balance.

The morphology of the plastic particles from fishing rope differed between polymer types and size classes. To describe and characterize the different morphologies, I used the following categorical definitions adapted from Rochman et al. (2019), but modified for the purpose of this study to specifically define particles that originated from fishing ropes. Threads; this term used for this study is defined as hard and flexible with equal thickness throughout with frayed or twisted endings. Thread bundles: a modified term adapted from the term fiber bundles from Rochman et al (2019), a cluster of individual threads that are difficult to untangle without damaging them. Fragments: a term adapted from Rochman et al (2019), is defined as subround/angular particles with an irregular shape and twisted/frayed endings that have varying heights, widths, and lengths.

3.3.6 Plastic fragmentation during rope breaking point

After completing all 40 experimental trials, I randomly selected five ropes of each polymer type to subject them to a breaking test (20 trials total). I used a Constant Rate of Transverse (CRT)

Tensile Test Machine to apply a pulling force on each rope while a high-speed camera (Kron Technologies, CH14-1.0-32C) captured the moment of breaking.

I cut ropes to a length of 1 m to fit into the machine and made eye splices on either end to connect to the Tensile Test Machine's lower stationary shackle and a hydraulically driven upper shackle. The shackles moved apart at a constant rate of 60 mm/minute (ISO, 2006). The tensile testing machine was calibrated to have a capacity of 10,160.5 kgf and the breaking strength was also recorded to determine the amount of force required to break, given the different stages of deterioration for each rope. The data recorded during each test was taken at 50 Hertz using a data acquisition software.

To visually capture fragmentation during breakage, I positioned the high-speed video camera 120 cm away from the tensile testing machine. It recorded with a resolution of 528 x 888 and 2021 frames-per-second. I illuminated the rope with a bright LED studio light and used a black backdrop to improve contrast and visibility of rope particles (Fig. 3.4).

I qualitatively assessed and analyzed video recordings of the snapping of each rope to describe fragmentation during rope destruction. I observed each video to understand how each rope responded during breaking and whether it emitted plastic particles upon breaking. Also, if there were plastics, I recorded their morphology (described above).

3.3.7 Statistical analysis

I conducted all statistical analysis in R Statistical Software (R Development Core Team, 2018). Polymer type is a covariate in the following analyses, that exhibits covariation with the dependent or response variable. It is a categorical variable which can be used in a linear regression, using the lm() function. This categorical variable was converted to be a nominal variable (1, 2, 3, 4) and displayed as box plots (Zuur et al., 2009). In the following statistical analyses, a linear regression was initially considered. If assumptions were violated, such as normality and heterogeneity, then a Kruskal-Wallis test was used.

3.3.7.1 Abrasion time vs. polymer type

I measured the diameter of ropes in between the five-minute intervals to determine when to conclude the trial (when rope diameters reached 50% of their original width due to material loss). To measure the effect of polymer type (*covariate*) on the amount of abrasion time (*response*) needed to break down the rope, I used a bivariate linear regression [Equation 1]. Validation revealed no violation of model assumptions.

$$
\begin{gathered}
Time_i \sim N(\mu_i, \sigma^2) \\
E(Time_i) = \mu_i \\
\mathrm{Var}(Time_i) = \sigma^2 \\
Time_i = \beta_o + Polymer_i
\end{gathered}
$$

(Eqn 1)

3.3.7.2 Total weight of plastics emitted vs. polymer type

I collected the plastic particles that had fragmented off of the ropes during the abrasion test between the five-minute intervals. To determine the total weight of plastics emitted at the end of each trial, I added all the weights from each five-minute interval. Our data had violated assumptions needed for an ANOVA due to the data having a non-distribution and heterogeneity of variance (Logan, 2011). Therefore, to measure the effect of polymer type (*covariate*) on the total weight of plastics emitted (*response)*, I used a Kruskal-Wallis test.

3.3.7.3 Rate of plastics emitted vs. polymer type

As each rope took different times to reach a 50% diameter loss, I also modeled the rate of total weight of plastics emitted per minute. The total weight of plastics emitted at the end of each trial was divided by the trial time to produce a rate of fragmentation. Our data had violated assumptions needed for an ANOVA due to the data having a non-normal distribution and heterogeneity of variance (Logan, 2011). Therefore, to measure the effect of polymer type on the rate of plastics emitted, I used a Kruskal-Wallis test.

3.3.7.4 Proportion vs. plastic size and polymer type

Each polymer rope emitted different size classes of plastic particles; microplastics (0.5 – 5 mm), mesoplastics (5 – 25 mm) and macroplastics (> 25 mm)(GESAMP, 2019; Rochman et al., 2015). To determine the proportion (response) of each plastic size (covariate) from the total weight emitted across polymer types (covariate), I used the non-parametric Aligned Ranks Transformation (ART) ANOVA (Salter & Fawcett, 1993). Prior to running the test, the weight of each polymer size was divided by trial time to control for the total. Our data had violated assumptions needed for a parametric test due to having a non-normal distribution and heterogeneity of variance during data exploration. Additionally, an ART ANOVA was used as I tested the interaction between the two covariates in order to determine the proportion of plastic sizes emitted within each polymer type (Wobbrock et al., 2011).

3.4 Results

3.4.1 Rate of rope diameter reduction from abrasion experiments

All polymer types reached a 50% diameter loss within two hours. Polymer type significantly affected the time taken to reach a 50% diameter loss ($F_{3,36} = 17.37$, $p < 0.001$ (Table 3.2)). Both PP and PP-PE polymers took longer on average to reach 50% diameter (40.5 min, and 19.5 min, respectively) while PA and PE took the least amount of time (Fig. 3.7). The duration of time it took to conclude each trial varied for each polymer type (Fig. 3.5). The amount of abrasion time for the ropes to reach a 50% diameter loss varied both within and across polymer types (Table 3.1). PP varied the most out of the four polymer types and on average took longer to deteriorate. PP-PE took the second longest with PE and PA both took the shortest average time to deteriorate.

3.4.2 Total Plastic loss from abrasion experiments

Polymer type had a significant impact on the total weight of plastics emitted ($\chi^2 = 14.674$, df = 3, p = < 0.05, Kruskal-Wallis test). To compare the different polymers and how they compare amongst each other, a Dunn's post hoc analysis was carried out to determine which polymer ropes are different in the mass of total plastics lost. Our results had found that both PP and PP-PE had emitted the most plastics whereas both PE and PA had emitted the least.

3.4.2 Rate of total plastic weight over trial time from abrasion experiments

A Kruskal-Wallis test showed there was no significant difference between the rate of plastic fragmentation (total plastics emitted divided by trial time) and the polymer types ($\chi^2 = 2.6824$, df = 3, p = 0.4432). This indicates that plastics emitting from the ropes is occurring at the same rate across all polymer types.

3.4.3 Change in rate of plastics emitted within abrasion experiments

All polymer types emitted plastic particles within each five-minute interval for every trial, including within the first five minutes (Fig. 3.6). As described above, over the course of the abrasion experiment, each polymer took different amounts of time to breakdown and lose 50% of its original diameter, indicating that some ropes are more robust than others. As shown in Fig. 3.5, the PE (range: 20 – 45 minutes) and PA (range: 20 – 50 minutes) rope lasted the shortest amount of time and had a steep drop in diameter loss towards the trial end. PP (range: 45 – 120 minutes) and PP-PE (range: 45 – 85 minutes) gradually deteriorated over time before the rope reached its end of life. These results coincided with the weight of plastics that were emitted within each five-minute interval (Fig. 3.6.). Where there was an acceleration of diameter loss, there was a corresponding spike in mass of plastics emitted. I had observed this towards the end of the trial as the ropes were reaching a diameter loss of 50%. This was notably pronounced with PA as there was some variation with how these ropes responded over the 10 trials; the ropes would either hold its shape and emit low levels of plastics overall or it would unravel or snap and cause a spike in plastic emissions.

3.4.4 Size class of plastic particles

The interaction between plastic size and polymer type had a significant impact on the proportion emitted ($F_6 = 13.78$, $p < 0.001$, ART ANOVA test). To compare and determine significant difference between the different plastic size classes within and across polymer types, a contrast analysis with a Tukey test was carried out. The Tukey test (multiple comparison test) was done in the R code to compare individual size classes within and across polymer types. As I was most interested in the relationship of each plastic size among polymer types, Table 3. 3 includes only these interactions from the model output. Among microplastics, PA and PE both emitted the lowest mass of particles with PP and PP-PE both emitting the most. There were no significant differences amongst the polymers for emitting different masses of mesoplastics. Among macroplastics, PA and PE both emitted the most plastic particles, followed by PP, with PP-PE emitting the least (Fig. 3.8).

3.4.5 Morphologies of plastic particles

The four polymer types emitted different morphologies of plastic particles (Fig. 3.9). Across all polymers, all of the microplastics were subround and/or subangular fragments. PE had a harder texture that emitted small fragments with a rigid structure and edges that were twisted. The other polymer types emitted off fragments characterized by flat flakes and frayed edges. The morphologies between the meso- and macroplastics were similar for PE, PP, and the PP-PE blend: all produced threads. However, PE created individual threads with equal thickness throughout while PA, PP, and PP-PE produced frayed thread bundles consisting of many individual threads that were tangled and could not be separated without damaging the threads.

PA thread bundles were made up of individual threads but held its uniform twisted rope shape, whereas the PP and PP-PE bundles were more tangled and clumped up together (Fig. 3.9).

3.4.6 Qualification of plastic fragmentation during breaking point

Footage of the ropes snapping showed particles coming off once the breaking point was reached as shown in Fig. 3.10 with the follow breaking loads: PE: 533.1 ± 78.2 kgf; PP: 1548.4± 298.6 kgf; PA: 596.9 ± 129.0 kgf; PP-PE: 946.0 ± 135.8 kgf. Upon snapping apart, the PA emitted a lot of thread bundles of twisted strands. PE emitted a scattering of individual threads (mainly macroplastics). PP and PP-PE responded similarly, generating a combination of individual plastic fragments (ranging from micro- to meso- plastics) and thread bundles (macroplastics).

3.5 Discussion

The goal of this study is to understand the response of each polymer rope in terms of plastic pollution in high-abrasion applications for fishing gear. This could inform decision-makers and stakeholders (i.e. fishers and gear manufactures) on which rope is appropriate depending on the context it is needed for. It was expected that some ropes would last longer than others and provide different outcomes during the rope abrasion and breakage test. This research has revealed that: 1) polymer type impacts the amount of abrasion time taken to deteriorate the ropes, 2) polymer type impacts the total weight of plastic particles emitted off of ropes, 3) polymer type does not impact the rate of plastic particle emission, 4) the plastic particle emission and rope deterioration trends within each trial varied across polymer types, 5) polymer types impact the proportion of plastic sizes emitted during abrasion, 6) plastic particles have different morphologies across polymer types during abrasion and breakage. These findings demonstrate that each polymer type responds differently under minimum amounts of tension and short duration of abrasion. Given that fishing gear is used in abrasive conditions in the marine environment on a frequent basis, this indicates that this is likely a prominent source of plastics debris polluting the oceans.

Our abrasion tests have shown that although the ropes took significantly different times to abrade to half of their original diameter, the rate of plastics emitted for each did not change. This means that polymer ropes that emit the most plastics in total, like PP and PP-PE, do so because they last longer in use; the same fragmentation rate for longer periods of times results in more plastic particles. Out of the four polymers, Polypropylene (PP) rope lasted the longest before it reached a 50% diameter loss, followed by PP-PE. Polymers that lasted the shortest amount of time, like PA and PE, created fewer plastic particles to be emitted but would require that ropes be replaced more frequently, which produces plastic waste of another kind. This study was adapted from the study, Welden & Cowie, (2017), and used weight to compare which polymers had emitted more. However, I recognize that each polymer's density is slightly different: PA (0.97-1.15 g/cm^3); PE (0.91-0.98 g/cm^3); PP (0.89-0.92g/cm^3); PP-PE (0.90-0.96g/cm^3)(Blumberg, 1993; Noel & Carley, 1975). Although comparing weights is a sufficient way to compare, taking densities into consideration should be done in future studies.

These complex results mirror existing research that finds each type of polymer rope as both pros and cons in different conditions. PA is known for its strong and elastic rope fibres but is also water absorbent and has a poor wet abrasion resistance. PA does not perform well in a wet state causing it to quickly breakdown as fatigue in the rope increases (Berger, 1994; Evans, 1983). PE has a bendable and elastic polymer construction, making it susceptible to surface fatigue and has a low abrasion resistance (Pejakovi et al., 2015). Overall, the results indicate that the ideal polymer rope to use and reduce plastic pollution may depend on the application than an inherent property of the rope that holds across all contexts (Table 3.4). For example, while PA and PE do not emit an overall large mass of plastic particles, their abrasion resistance is low compared to PP and PP-PE and would not be ideal in highly abrasive areas where they might break, lose gear out at sea and result in ghost fishing. Other plastics such as PP and PP-PE might reduce the chances of losing gear, but they create more fragmented microplastics, which can impact sensitive species. Bivalves, for example, are known to ingest small microplastics (Bour et al., 2018; Van Cauwenberghe & Janssen, 2014), raising contamination concerns for mussel farms if PP and PP-PE are used in nearby abrasive areas.

In the event that strained ropes break at sea, the high-speed camera videos demonstrated that not only do ropes emit plastic particles upon failure, but that they differed by size and morphology between polymer types. After undergoing strain from the tensile testing machine during the breakage test, PA had emitted bundled threads and PE emitted a scattering of individual threads (particularly macroplastics). The effects of the abrasion tests were also reflected in the breaking load tests; the PE and PA required the least amount of force to break the ropes apart, respectively, with PP requiring the largest amount of force, followed by PP-PE. Both of these phenomena for PE and PA was similar in the abrasion test as the deteriorated ropes lost its shape as it neared the end of the trial. PP and PP-PE had also emitted a combination of different types of plastic particles (in morphology and size). While ghost fishing from derelict fishing gear is a consequence of rope failure, the emission of plastic particles is another method of pollution that can impact marine biota.

While it has been previously speculated that bottom-contact abrasion contributes to plastic particle emission (Seo et al., 1997; N. A. Welden & Cowie, 2017), this study provides empirical evidence for the weight and morphology of plastics that are emitted from fragmentation during fishing gear use in a simulated benthic environment. Moreover, I provide details of polymer rope response throughout their lifespan while subjected to abrasion and then snapping by observing and categorizing the types and sizes of plastics emitted. The different sizes (micro-, meso- and macro-) emitted from this experiment is important to understand as plastic pollution literature is clear that different size classes of plastics present different types of harm to biota and environments (Bucci et al., 2020). Additionally, the mass of plastics emitted into the ocean by each polymer also gives a better understanding of where in the ocean the plastics are ending up in. Polymer types such as PP, PE, and PP-PE are less dense than water and float, whereas PA is denser than water and sinks. Polymer buoyancy can determine where plastics will be within the water column (Kooi et al., 2016). So, the plastics emitted from PP, PE, and PP-PE will be located in shallower depths of the ocean. PA sinks and will most likely be found in the benthic environment and putting benthic organisms at risk of ingesting them (Andrady, 2011).

The limitations of this experiment include the decision to collect plastics larger than 0.5 mm in size due to the large scale of the setup. Plastics have the ability to break down into much smaller sizes, including the nanoscale, but detection becomes unreliable or impossible with the naked eye. Other studies might pursue observation of plastics smaller than 0.5 mm. Our experiment was also limited to subjecting the ropes to an abrasive surface of a simulated benthic environment. Other environmental factors such as UV radiation, temperature, mechanical wave action are all factors that have been used in other experiments to subject the ropes to additional stressors that could influence the weight and rate of plastic particles emitted, especially if ropes are exposed to multiple, combined factors.

I invite researchers to model the mass of plastic particles emitted by the fishing industry during operations. Currently, contemporary research has primarily investigated derelict gear as fisheries' main plastic waste but fails to include fragmented plastics emitted during operations. How much each polymer rope can fragment within its lifetime can also be modelled based on these results. Fishing gear innovation is designed through technological improvements to not only optimize catch efficiency but to also reduce ecological impact (Suuronen et al., 2012). Our study results may also be useful to designers and technologists aiming to improve the longevity and abrasion resistance of ropes while reducing fragmentation rates.

3.6 Tables

Table 3. 1 The average amount of abrasion time for ropes to reach 50% diameter loss.

Polymer Type	Minutes (Mean ± SE)	Range
PA	36.5 ± 3.0	20 – 50
PE	34 ± 2.4	20 – 45
PP	77 ± 7.6	45 – 120
PP-PE	56.5 ± 4.3	45 – 85

Table 3. 2 Model output from equation 1. Estimated regression parameters, standard errors, t-values and P-values

	Estimate	Std. Error	t value	P-value
Intercept	36.500	4.799	7.605	4.37e-09
PolymerPE	-2.500	6.787	-0.368	0.71479
PolymerPP	40.500	6.787	5.967	7.69e-07
PolymerPP-PE	19.500	6.787	2.873	0.00678

Table 3. 3 Model output with multiple comparisons from tukey test for proportion of size class among the four polymer types.

	Df	Df. Res	F value	Pr(>F)	
Plastic Size	2	108	33.61436	4.4689e-12	
Polymer Type	3	108	0.35324	0.78688	
Plastic Size: Polymer Type	6	108	13.78044	1.4139e-11	
Contrast	**Estimate**	**SE**	**Df**	**t.ratio**	**p.value**
Macro, PA – Macro, PE	-14.6	12.1	108	-1.206	0.9875
Macro, PA – Macro, PP	21.6	12.1	108	1.784	0.8231
Macro, PA – Macro, PP-PE	40.8	12.1	108	3.370	0.0461
Meso, PA – Meso, PE	-1.7	12.1	108	-0.140	1.0000
Meso, PA – Meso, PP	11.1	12.1	108	0.917	0.9988
Meso, PA – Meso, PP-PE	18.2	12.1	108	1.503	0.9367
Micro, PA – Micro, PE	-12.2	12.1	108	-1.008	0.9972
Micro, PA – Micro, PP	-62.4	12.1	108	-5.153	0.0001
Micro, PA – Micro, PP-PE	-76.8	12.1	108	-6.343	<0.0001
Macro, PE – Macro, PP	36.2	12.1	108	2.990	0.1261
Macro, PE – Macro, PP-PE	55.4	12.1	108	4.575	0.0008
Meso, PE – Meso, PP	12.8	12.1	108	1.057	0.9958
Meso, PE – Meso, PP-PE	19.9	12.1	108	1.643	0.8887
Micro, PE – Micro, PP	-50.2	12.1	108	-4.146	0.0037
Micro, PE – Micro, PP-PE	-64.6	12.1	108	-5.335	<0.0001
Macro, PP – Macro, PP-PE	19.2	12.1	108	1.586	0.9106
Meso, PP – Meso, PP-PE	7.1	12.1	108	0.586	1.0000
Micro, PP – Micro, PP-PE	-14.4	12.1	108	-1.189	0.9888

Table 3. 4 Results from abrasion and breakage experiment

	Shortest	Medium	Longest
Length of time taken to reach 50% diameter loss	PA, PE	PP-PE	PP
	Lowest	Medium	Highest
Total weight of plastic particles emitted	PA, PE	No Trend	PP, PP-PE
	Lowest	Medium	Highest
Proportion of Total weight of plastic particles containing Microplastics	PA, PE	No Trend	PP, PP-PE
Proportion of Total weight of plastic particles containing Mesoplastics	No Trend	No Trend	No Trend
Proportion of Total weight of plastic particles containing Macroplastics	PP-PE	PP	PA, PE
	Fragments	Individual Threads	Thread Bundles
Plastic morphology emitted from rope abrasion experiment	PA, PE, PP, PP-PE	PE	PA, PP, PP-PE
Plastic morphology emitted from rope breakage test	PP, PP-PE	PE	PA, PP, PP-PE

3.7 Figures

Fig. 3. 1 Artificial Seabed Platform

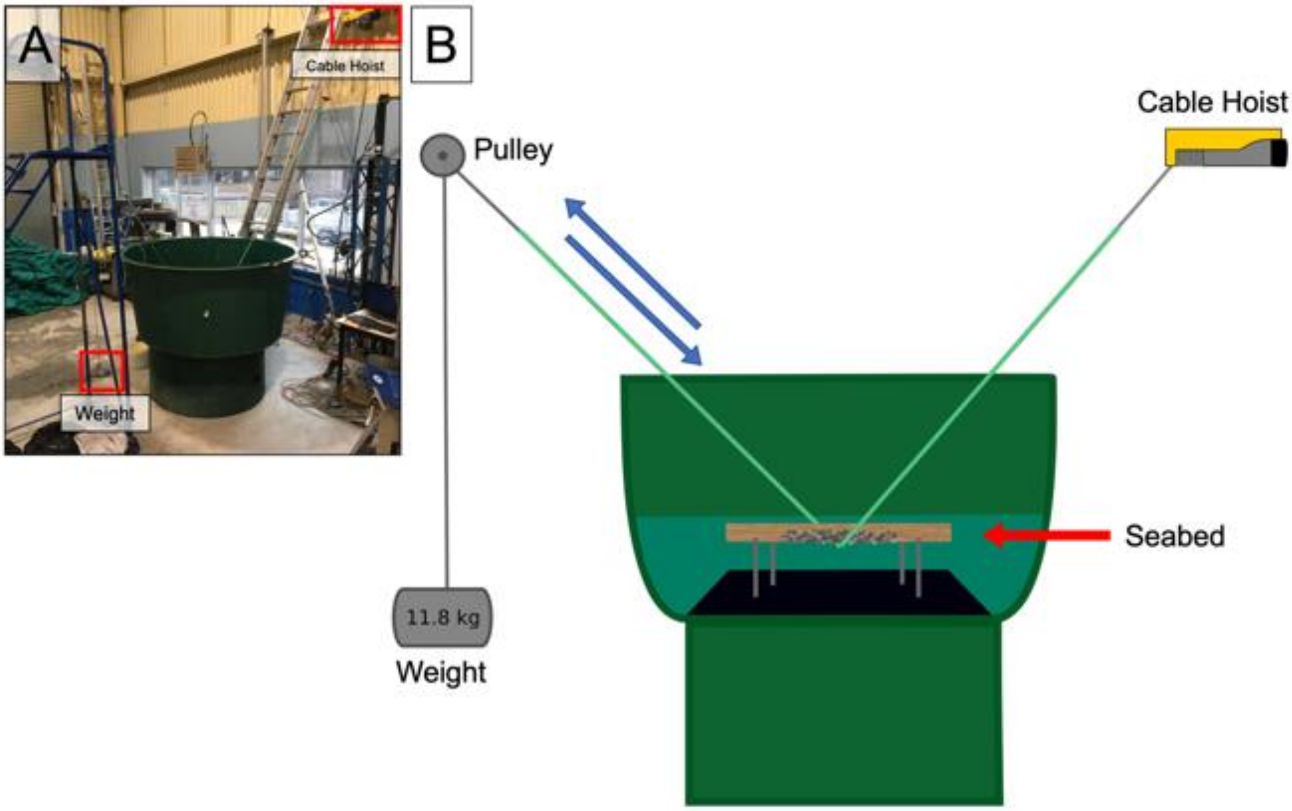


Fig. 3. 2 Abrasion Apparatus Experimental Setup

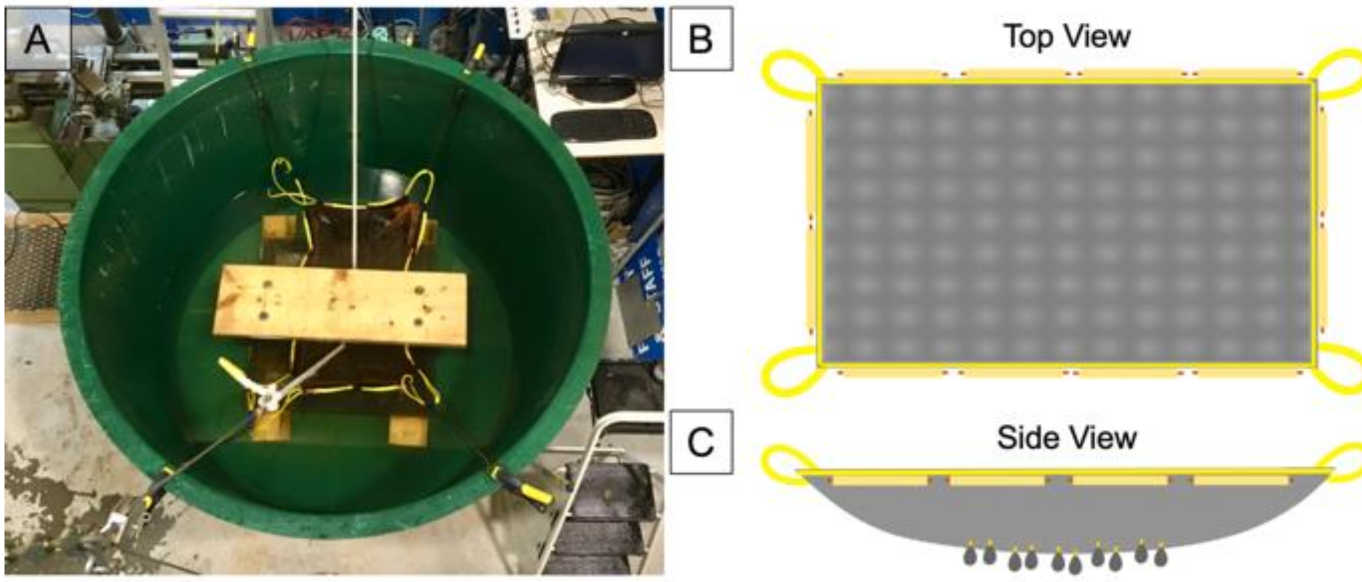


Fig. 3. 3 Net used to catch Nylon (PA) particles. (A) shows the net positioned under the seabed to capture falling particles. (B) Top-view and (C) side-view of the net used to catch PA plastic particles.

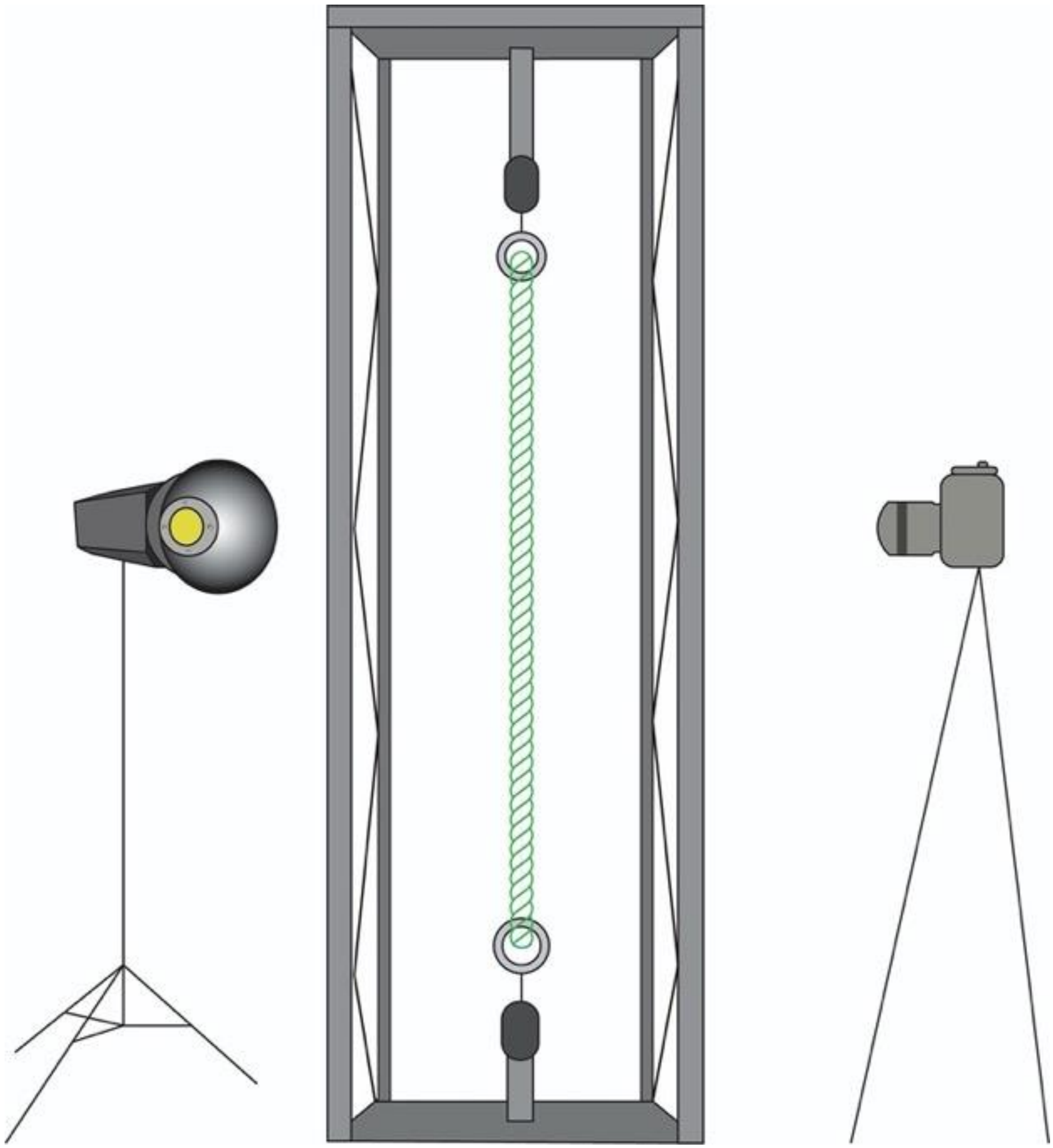


Fig. 3. 4 Breaking point experimental set-up with tensile testing machine and high-speed camera

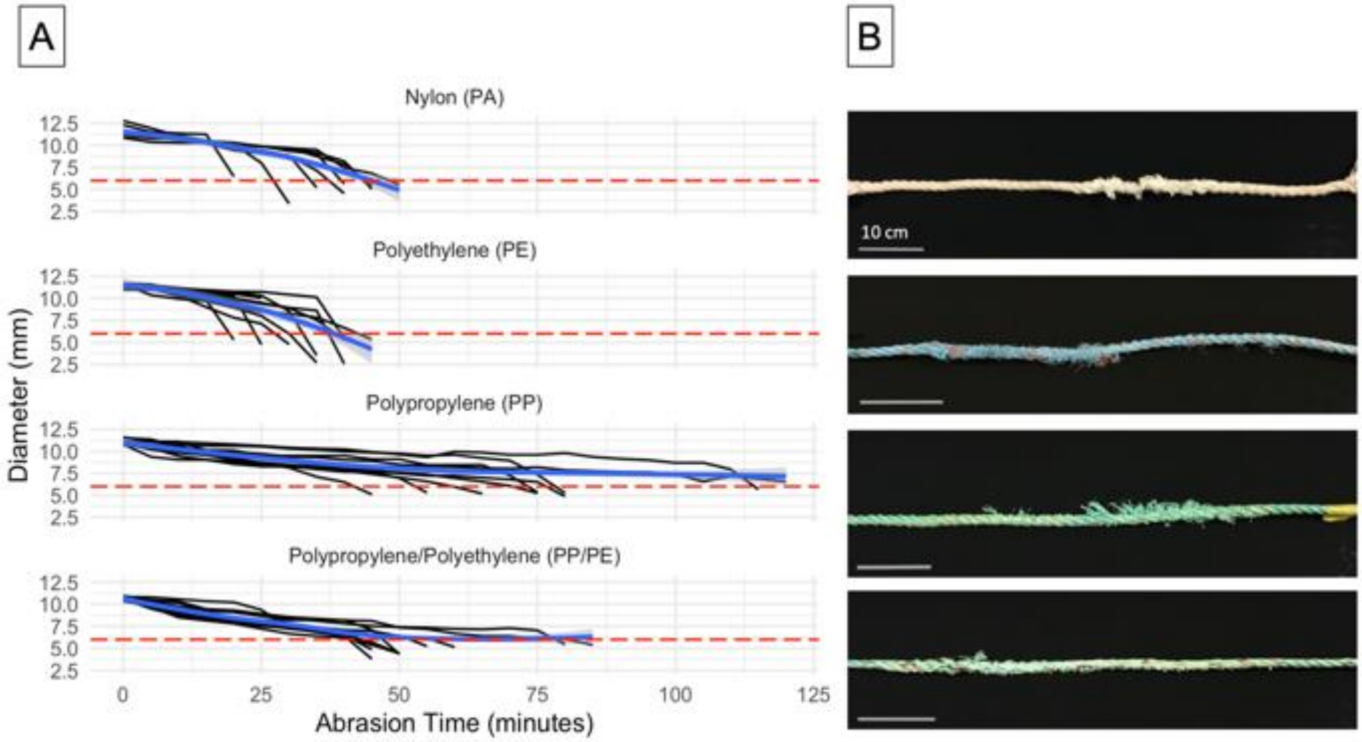


Fig. 3. 5 The deterioration of the diameter for each polymer rope type. A) The rate of diameter decreasing during abrasion trials for each polymer type. The black lines show the deterioration trend for each trial. The smoothed blue line in each plot is the LOESS smoother to aid in visual interpretation for the 10 trials. The red lines in each plot indicate the 50% diameter loss line. B) Image of abraded rope sample after completed trial. The scale bar is 10 cm for each image.

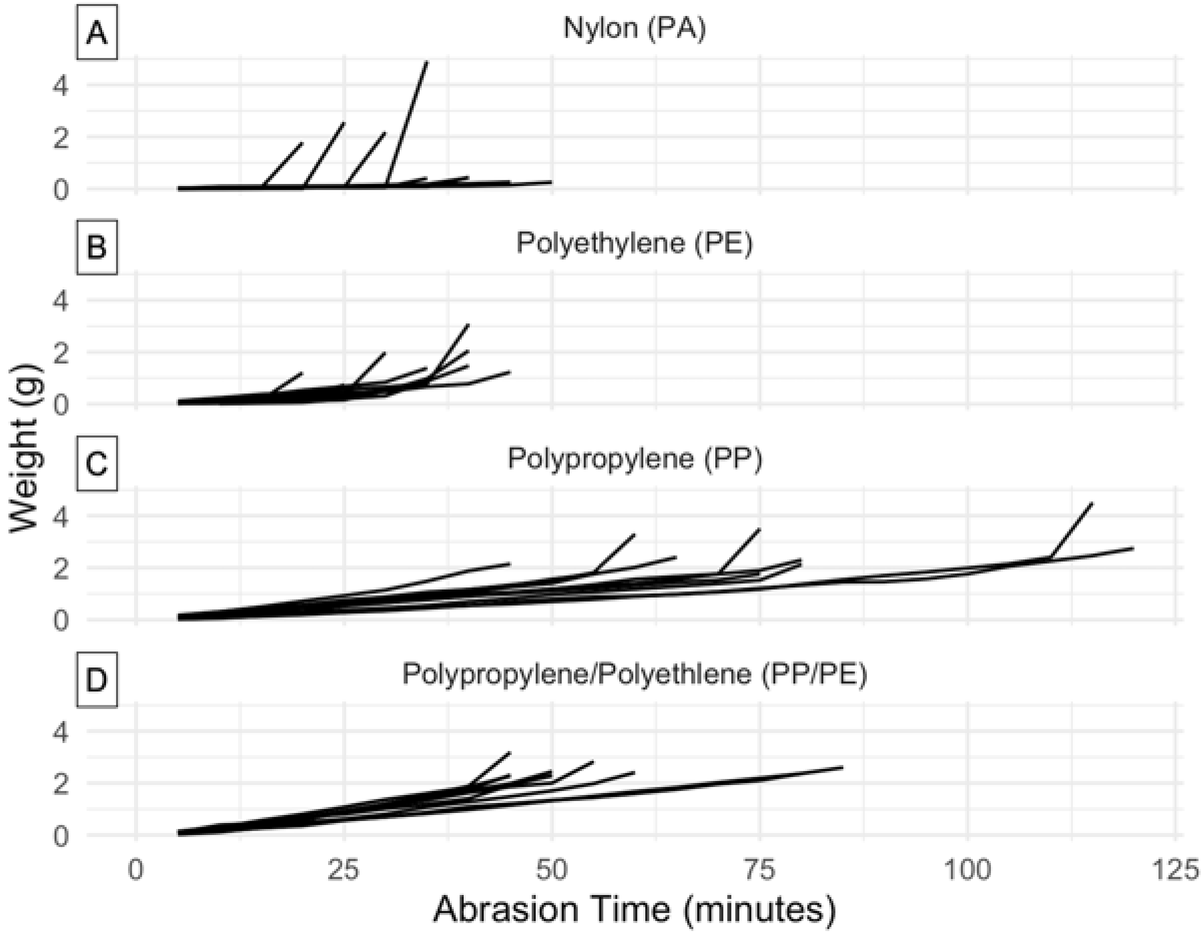


Fig. 3. 6 The accumulation of plastics particles (by weight) emitted from each polymer type. The polymer types tested include A) Nylon; B) Polyethylene; C) Polypropylene; D) Polypropylene-Polyethylene. The black lines show the plastic emission trend for each trial.

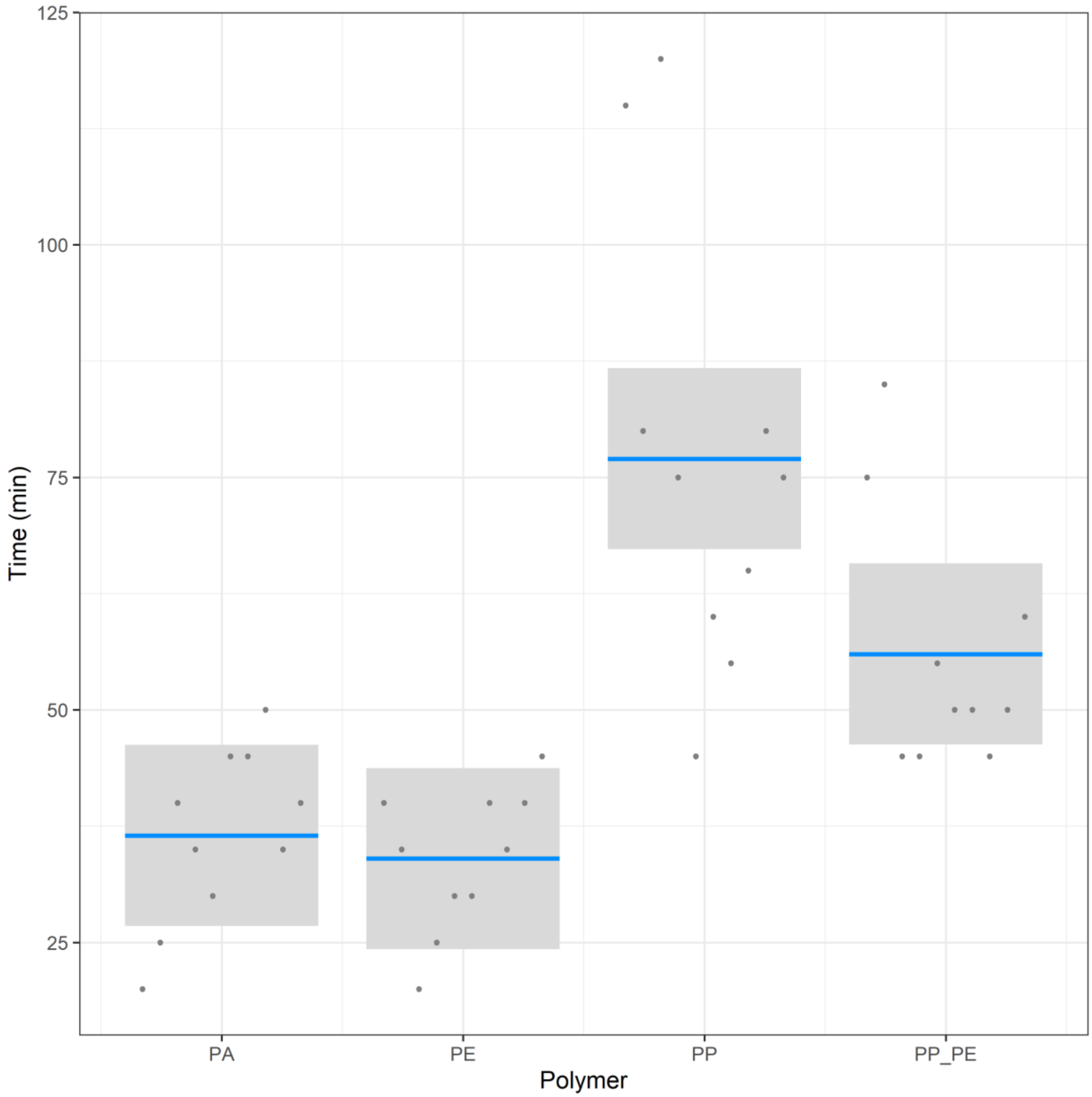


Fig. 3. 7 Visualization of the linear regression model output for the amount of abrasion time (continuous response variable) required to deteriorate the ropes to reach a dimeter loss by 50% for each polymer type (categorical covariate variable). Dots represent the individual data points, blue line represents the expected values and the grey area is the confidence interval.

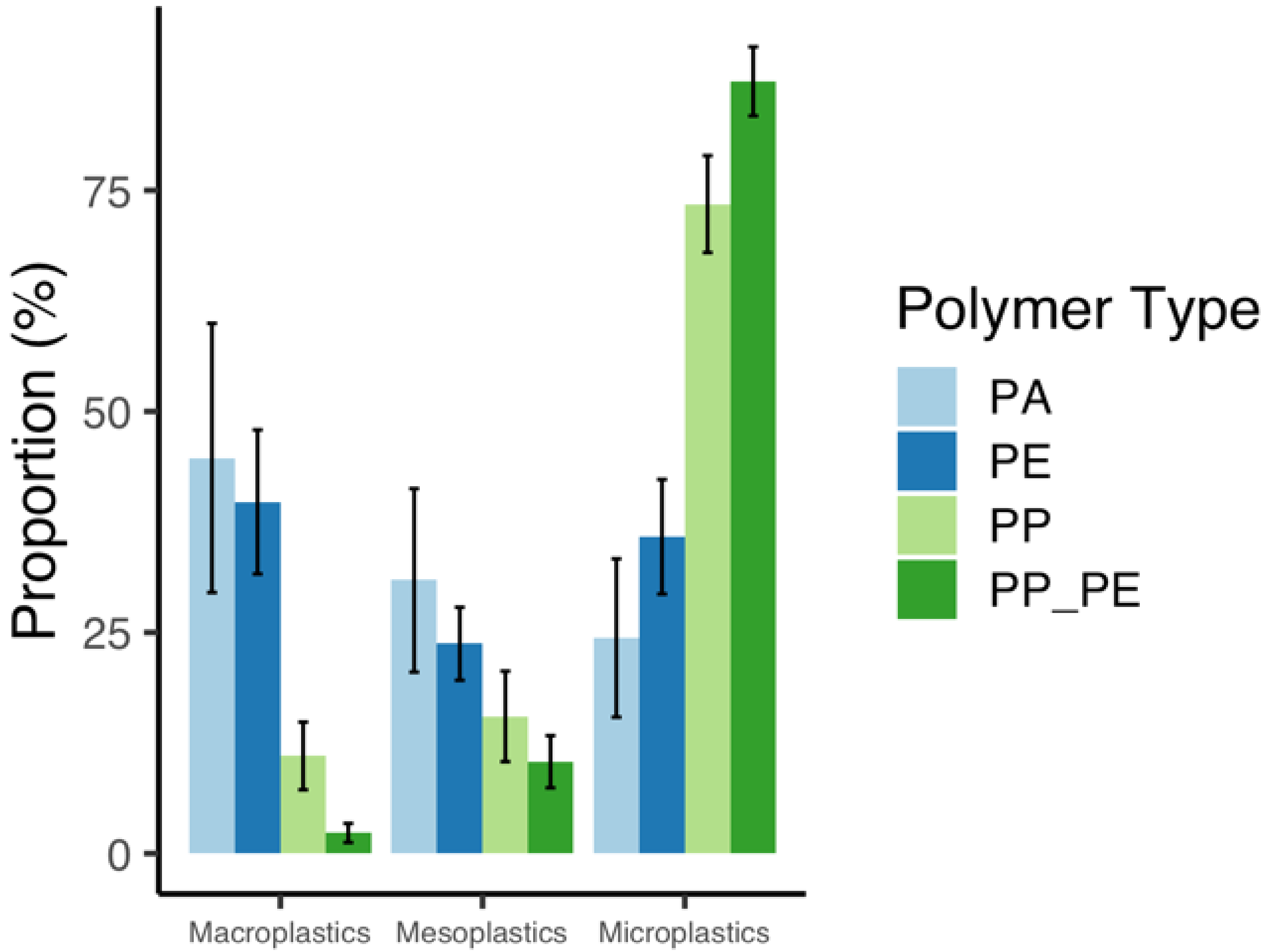


Fig. 3. 8 Proportion of each polymer size for the different polymer types from the abrasion experiment. Three plastic sizes; micro- (0.5 – 5 mm), meso- (5 – 25 mm), macro- (> 25 mm).

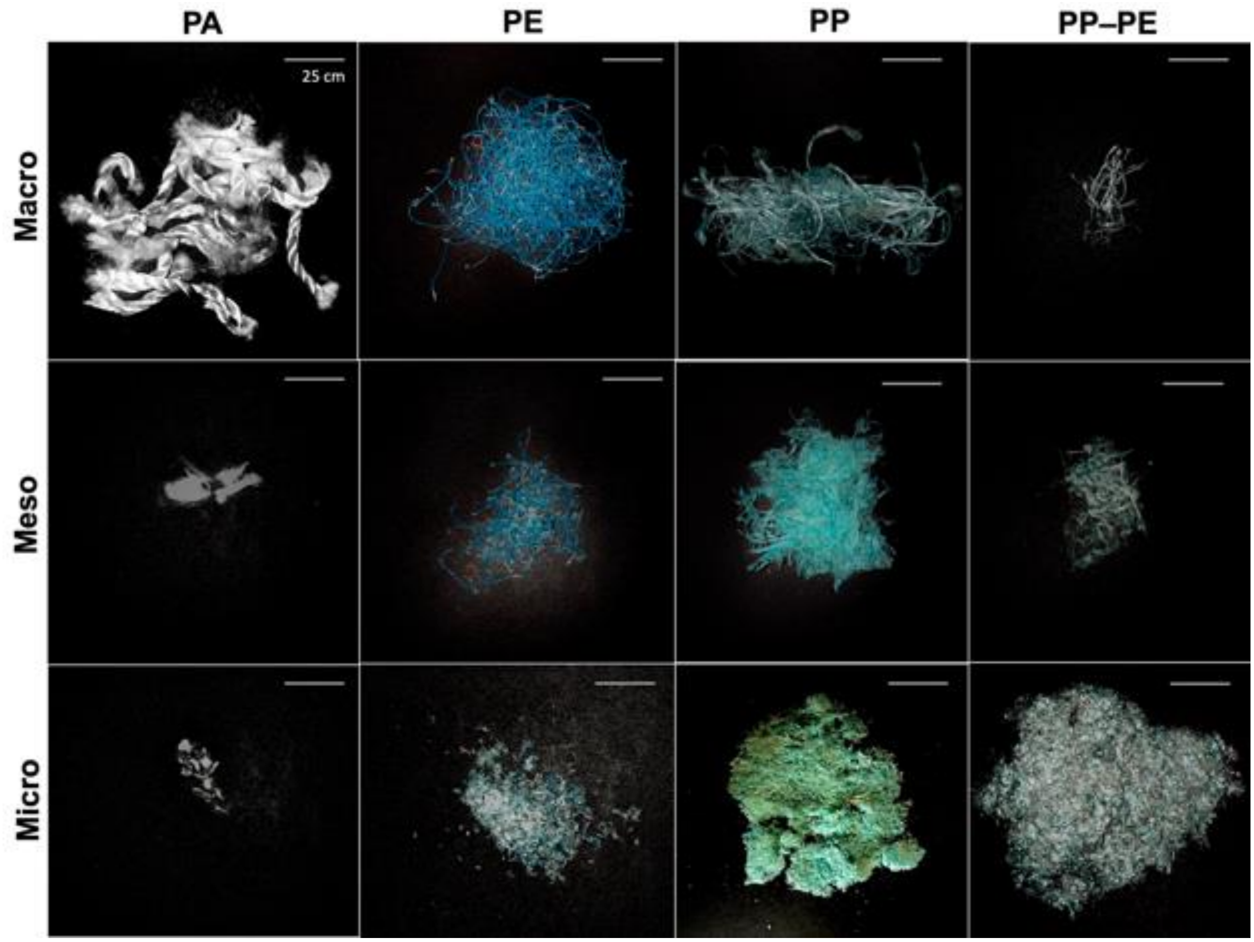


Fig. 3. 9 Images of each polymer type and the size classes. The different polymers are separated by the four columns: Nylon (PA) is the first column; Polyethylene (PE) is the second column; Polypropylene (PP) is the third column; and Polypropylene-polyethylene blend (PP-PE) is the last column on the right. The three rows display the average accumulated weight of plastics for each size class; Macroplastics (> 25 mm) in the first row; Mesoplastics (5 – 25 mm) in the second row; Microplastics in the bottom row. The scale bar is 25 mm for each image.

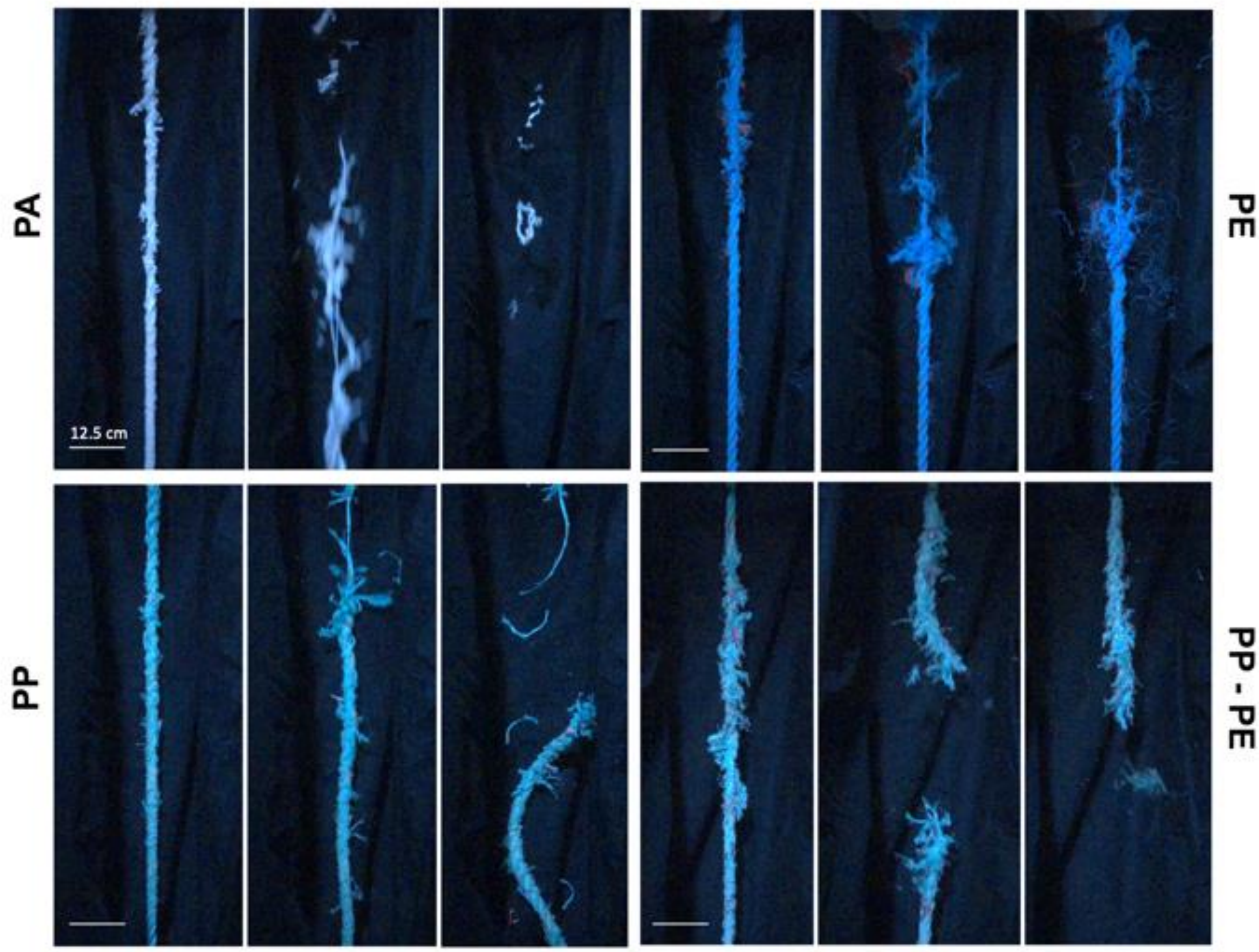


Fig. 3. 10 Images of a sample of each polymer rope. Nylon (PA) in the top left panel; Polyethylene (PE) in the top left panel; Polypropylene (PP) in the bottom left panel; Polypropylene-polyethylene blend (PP-PE) in the right bottom panel. Each panel displays the abraded rope before, during, and after reaching the breaking point and shedding plastic particles. The scale bar is 12.5 cm for each panel.

Chapter 4: General Discussion

4.1 Summary

Fishing gear-related plastic debris is harmful to the marine environment and is challenging and costly to recover (Macfadyen et al., 2009). Fishing gear is frequently used in abrasive conditions which results in fragmentation of small plastic particles, which makes mitigation and reducing plastic pollution a challenging endeavour. Given that fisheries are dependent on a healthy marine environment, the issue grants sufficient urgency to identify and address pollution entry points contributed by this industry.

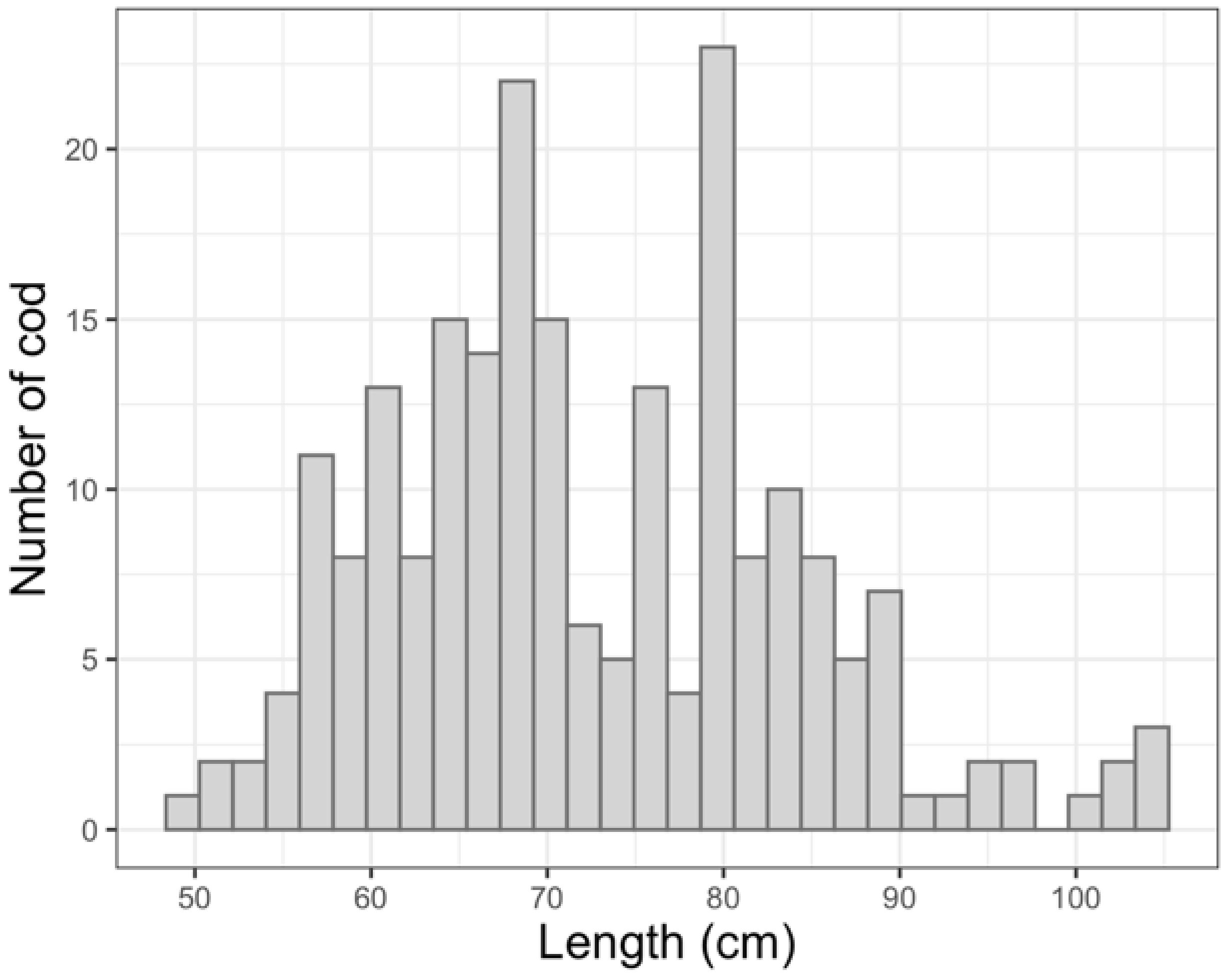
Our complimentary studies demonstrated first that plastic fishing gear and plastic threads that may be from fishing are ingested by Atlantic Cod, a commercially important species caught in an area with high commercial fishing activity. These results indicate fishing gear related plastics, such as bait bags, can be ingested by target species without having been abandoned or lost at sea. Indeed, plastics had been ingested by a target species directly from the gear meant to capture them. It also indicates that some forms of plastic pollution are likely threads from ropes and other gear. To further investigate the origins of plastics from in-use fishing gear, I then investigated the relationship between gear used during fishing operations and the types and rates of polymer particles emitted. I found that even at the earliest stages of abrasive use, fishing gear play a predominant role in producing plastic particles during fishing operations and as such may be subsequently impacting commercial fish in Newfoundland and Labrador. Based on these studies, preventative measures would include monitoring fishing gear for potential fragmentation or emission of gear parts that are not properly secured.

Future research may be aimed at designing gear to reduce its input of fragmented plastic debris, extending and complimenting existing design testing strategies that mainly focus on tensile strength. In 2018, The Canadian government issued a grant called the Plastics Challenge – Sustainable Fishing and Aquaculture Gear through the Innovative, Science and Economic Development Canada program, incentivizing researchers and gear manufacturers to develop research projects aimed at improving fishing gear in reducing its environmental impact through plastic pollution (Fisheries and Oceans Canada, 2018). Given the benefits of synthetic fibres, immediate action should be geared towards modifications coupled with more research to find a true biodegradable option. The frequent use of fishing gear makes it impossible for complete prevention of plastic pollution given the abrasive conditions that fishing gear have to endure in such a harsh environment. In addition to immediate gear modifications, eventually developing a rope material alternative to replace plastic polymers and still optimize on catch efficiency, would provide the ideal outcome to combat plastic pollution. Until then, more research and development in material science will need to be made to create an ideal rope alternative.

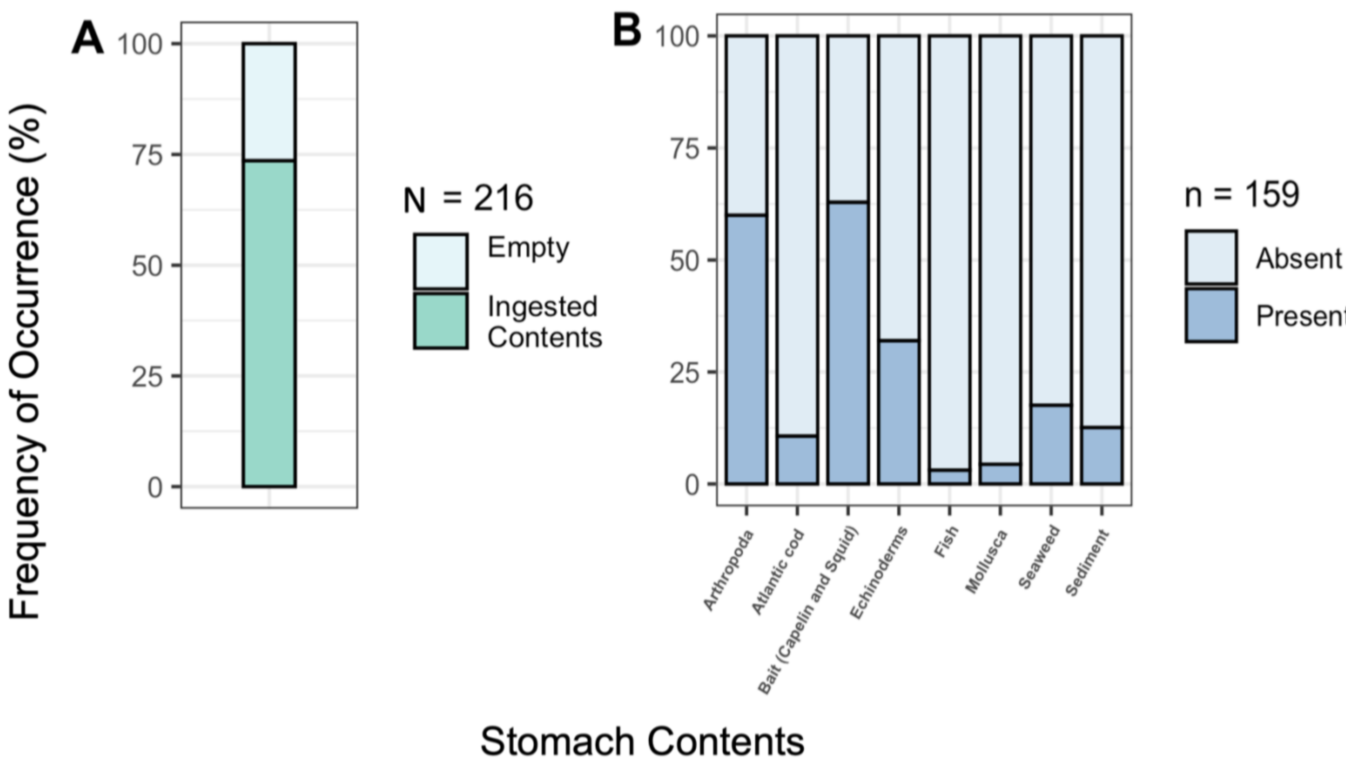
Appendices

Chapter 2:

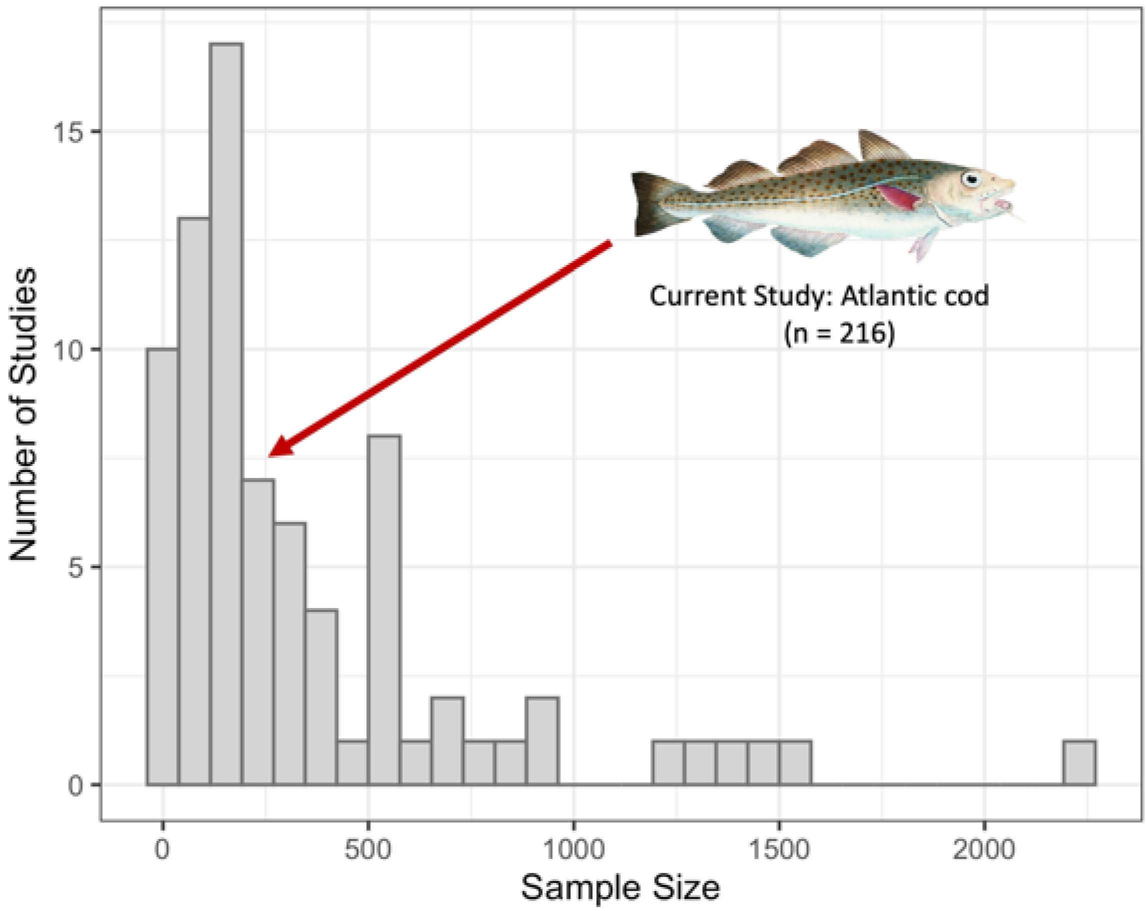
Appx 2. 1: Histogram showing the fork length of all the individual Atlantic cod (N = 216).



Appx 2. 2: Stomach contents of Atlantic cod. (A) The frequency of occurrence (%) of the presence and absence for each ingested content within 159 individuals. (B) A comparison between the number of individuals with empty stomachs (n = 57) with the individuals that had stomach contents (n = 159).



Appx 2. 3: Histogram showing the number of fish sampled in each study previously gathered and reviewed by (Markic et al., 2019) and (F. Liboiron et al., 2018), and indicating the sample size of the present study. Public domain Atlantic cod image from New York Public Library.

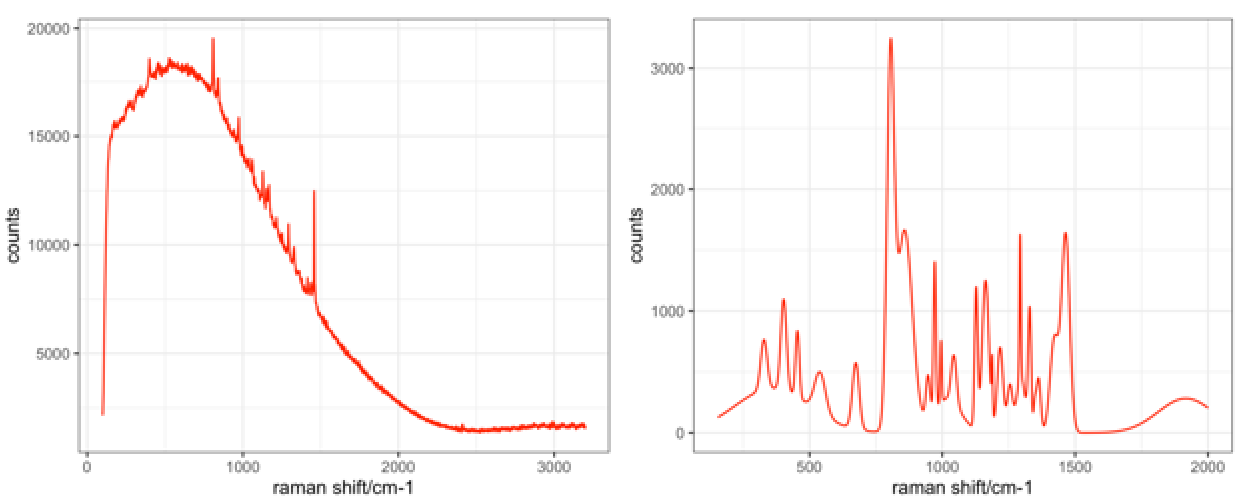


Raman Spectroscopy

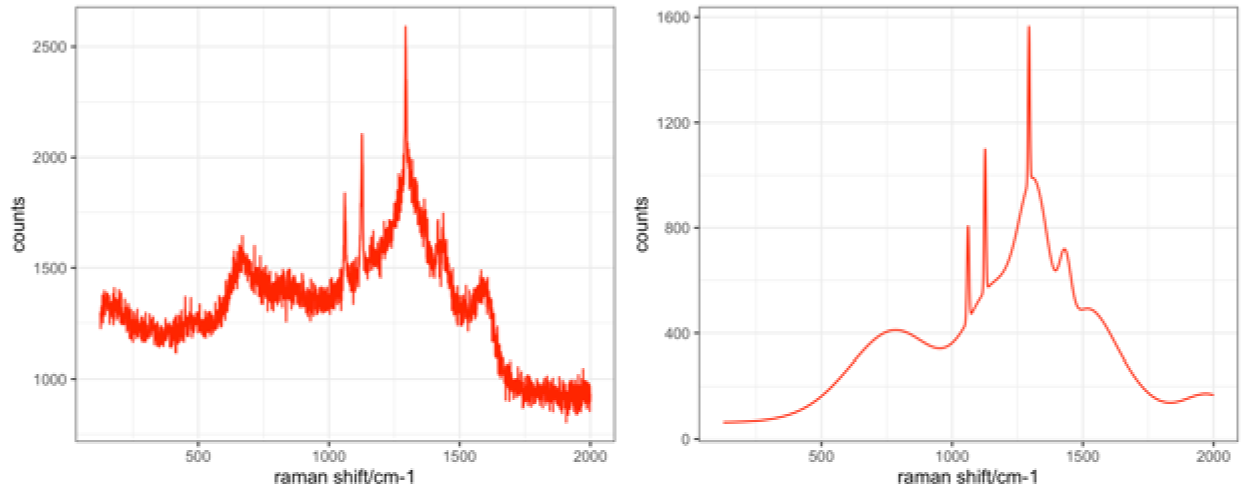
One thread out of 216 GI tract samples was analyzed using Raman micro-spectrometry and was identified as polypropylene.

Appx 2. 4: Raw raman spectra data generated from the spectrometer of the three samples on the left with the smoothed spectra on the right. For easier interpretation, the spectra had undergone a deconvoluted process using the open-source software Fityk to perform a curve and peak fitting using a Gaussian function. The peaks were compared with published polymer spectras such as polyethylene, polyester, polycarbonate, PVC, polyamide, and polypropylene. **(A)** Thread sample found within the GI tract of a 69 cm male cod. The peak patterns were matched with polypropylene. **(B)** Black netting from bait bag found within the GI tract of a 96 cm female cod. **(C)** Black netting from bait bag found within the GI tract of a 70 cm female cod. The peak patterns from both B and C were matched with polyethylene.

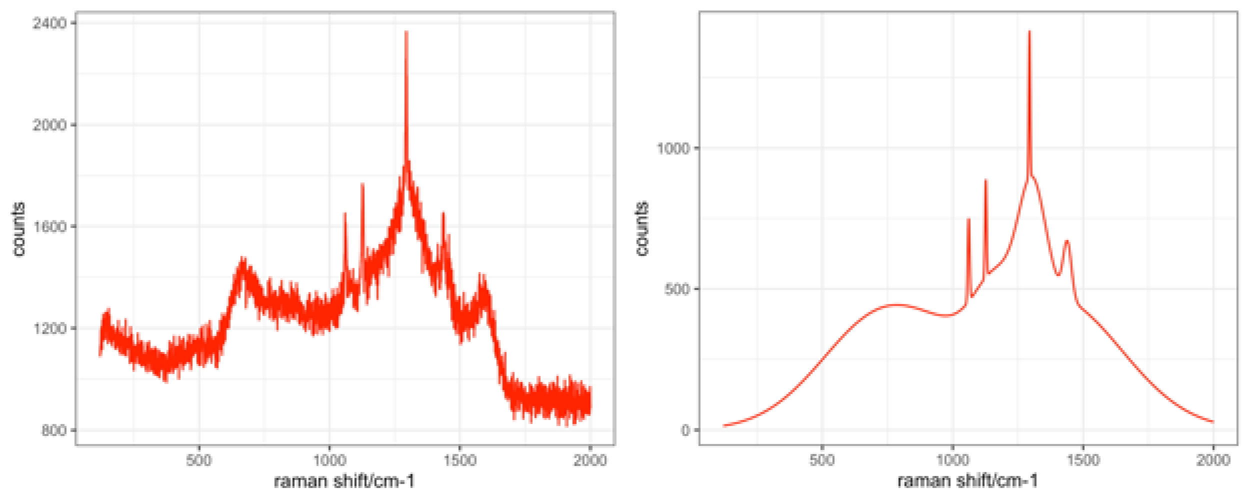
A



B



C



Chapter 3:

Appx 3. 1: Python Code for Rope Abrasion Experiment

```
import RPi. GPIO as GPIO
import time
GPIO.setwarnings(False)
GPIO.setup(11, GPIO.OUT)
GPIO.setup(13, GPIO.OUT)
GPIO.setup(15, GPIO.OUT)
GPIO.setup(29, GPIO.OUT)

#Start with cable hoist off
GPIO.output(11, True)
```

```
GPIO.output(13, True)
GPIO.output(15, True)
GPIO.output(29, True)
time.sleep(2)
#Run program for 2 hours
For i in range(1):

     #Cable hoist run for 5 minutes
     for i in range(38):

          #Cable hoist down
          GPIO:output(11, True)
          GPIO.output(13, False)
          GPIO.output(15, False)
          GPIO.output(29, True)
          time.sleep(2)

          #Cable hoist off
          GPIO.output(11, True)
          GPIO.output(13, True)
          GPIO.output(15, True)
          GPIO.output(29, True)
          time.sleep(2)

          #Cable hoist up
          GPIO.output(11, False)
          GPIO.output(13, True)
          GPIO.output(15, True)
          GPIO.output(29, False)
          time.sleep(3)

          #Cable hoist off
          GPIO.output(11, True)
          GPIO.output(13, True)
          GPIO.output(15, True)
          GPIO.output(29, True)
          time.sleep(2)

#Cable hoist rest for two minutes
time.sleep(120)
```

Literature Cited:

Ahmed, S. F., Moon, M., Kim, C., Jang, Y., Han, S., Park, W., … Jang, Y. (2010). Optical properties of surface modified polypropylene by plasma immersion ion implantation technique. *Applied Physics Letters*, *97*(8), 081908. https://doi.org/10.1063/1.3481417

Albertsson, A., & Karlsson, S. (1988). The three stages in degradation of polymers—polyethylene as a model substance. *Journal of Applied Polymer Science*, *35*(5), 1289–1302. https://doi.org/10.1002/app.1988.070350515

Andrady, A. L. (2011). Microplastics in the marine environment. *Marine Pollution Bulletin*, *62*(8), 1596–1605. https://doi.org/10.1016/j.marpolbul.2011.05.030

Andrady, A. L., & Neal, M. A. (2009). Applications and societal benefits of plastics. *Philosophical Transactions of the Royal Society B: Biological Sciences*, *364*(1526), 1977–1984. https://doi.org/10.1098/rstb.2008.0304

Arthur, C., Sutton-Grier, A. E., Murphy, P., & Bamford, H. (2014). Out of sight but not out of mind: Harmful effects of derelict traps in selected U.S. coastal waters. *Marine Pollution Bulletin*, *86*(1–2), 19–28. https://doi.org/10.1016/j.marpolbul.2014.06.050

Backer, S., McGarry, F. ., & Williams Jr., J. . (1981). *Deterioration of Synthetic Fiber Rope During Marine Usage*. *Massachusetts Institute of Technology*. Cambridge, Massachusetts.

Barboza, L. G. A., Dick Vethaak, A., Lavorante, B. R. B. O., Lundebye, A. K., & Guilhermino, L. (2018). Marine microplastic debris: An emerging issue for food security, food safety and human health. *Marine Pollution Bulletin*, *133*, 336–348. https://doi.org/10.1016/j.marpolbul.2018.05.047

Barnes, D. K. A., Galgani, F., Thompson, R. C., Barlaz, M., Barnes, D. K. A., Galgani, F., … Barlaz, M. (2009). Accumulation and fragmentation of plastic debris in global environments. *Philosophical Transactions of the Royal Society B: Biological Sciences*, *364*(1526), 1985–1998. https://doi.org/10.1098/rstb.2008.0205

Baum, J. K., & Fuller, S. D. (2016). *Canada's marine fisheries: status, recovery potential and pathways to success*. *Oceana*. Retrieved from https://www.oceana.ca/en/publications/reports/canadas-marine-fisheries-status-recovery-potential-and-pathways-success

Benjamins, S., Ledwell, W., Huntington, J., & Davidson, A. R. (2012). Assessing changes in numbers and distribution of large whale entanglements in Newfoundland and Labrador, Canada1. *Marine Mammal Science*, *28*(3), 579–601. https://doi.org/10.1111/j.1748-7692.2011.00511.x

Berger, G. A. (1994). *U.S. Patent No. 5333442*. Washington DC. Retrieved from https://patents.google.com/patent/US5333442A/en

Black, G. A. P., Rowell, T. W., & Dawe, E. G. (1987). *Atlas of the biology and distribution of the squids Illex illecebrosus and Loligo pealei in the Northwest Atlantic*. Ottawa, Canada: Department of Fisheries and Oceans.

Blumberg, A. A. (1993). Products of chemistry - Identifying polymers through combustion and density. *Journal of Chemical Education*, *70*(5), 399–403. https://doi.org/10.1021/ed070p399

Bond, A. L., Montevecchi, W. A., Guse, N., Regular, P. M., Garthe, S., & Rail, J. F. (2012). Prevalence and composition of fishing gear debris in the nests of northern gannets (Morus bassanus) are related to fishing effort. *Marine Pollution Bulletin*, *64*(5), 907–911. https://doi.org/10.1016/j.marpolbul.2012.03.011

Bour, A., Haarr, A., Keiter, S., & Hylland, K. (2018). Environmentally relevant microplastic exposure affects sediment-dwelling bivalves. *Environmental Pollution*, *236*, 652–660. https://doi.org/10.1016/j.envpol.2018.02.006

Bråte, I. L. N., Eidsvoll, D. P., Steindal, C. C., & Thomas, K. V. (2016). Plastic ingestion by Atlantic cod (Gadus morhua) from the Norwegian coast. *Marine Pollution Bulletinm*, *112*(1–2), 105–110. https://doi.org/10.1016/j.marpolbul.2016.08.034

Brothers, G. (1992). *Lost or abandoned fishing gear in the Newfoundland aquatic environment*. St. John's, NL, Canada: Fisheries & Habitat Management, Department of Fisheries & Oceans.

Bucci, K., Tulio, M., & Rochman, C. M. (2020). What is known and unknown about the effects of plastic pollution: A meta-analysis and systematic review. *Ecological Applications*, *30*(2), 1–16. https://doi.org/10.1002/eap.2044

Choy, C. A., Robison, B. H., Gagne, T. O., Erwin, B., Firl, E., Halden, R. U., … S. Van Houtan, K. (2019). The vertical distribution and biological transport of marine microplastics across the epipelagic and mesopelagic water column. *Scientific Reports*, *9*(1), 1–9. https://doi.org/10.1038/s41598-019-44117-2

Clunies-Ross, P. J., Smith, G. P. S., Gordon, K. C., & Gaw, S. (2016). Synthetic shorelines in New Zealand? Quantification and characterisation of microplastic pollution on Canterbury's coastlines. *New Zealand Journal of Marine and Freshwater Research*, *50*(2), 317–325. https://doi.org/10.1080/00288330.2015.1132747

Cole, M., Lindeque, P., Halsband, C., & Galloway, T. S. (2011). Microplastics as contaminants in the marine environment: A review. *Marine Pollution Bulletin, 62*(12), 2588–2597. https://doi.org/10.1016/j.marpolbul.2011.09.025

Corcoran, P. L. (2015). Benthic plastic debris in marine and fresh water environments. *Environmental Science: Processes Impacts, 17*, 1363–1369. https://doi.org/10.1039/c5em00188a

Corey, K. E., Wilson, M. I., & Corey, M. J. (2014). *A model for rural development: an experiment from Fogo Island, Newfoundland*. East Lansing, Michigan: Michigan State University Libraries.

Dantas, D. V., Barletta, M., & da Costa, M. F. (2012). The seasonal and spatial patterns of ingestion of polyfilament nylon fragments by estuarine drums (Sciaenidae). *Environmental Science and Pollution Research*, *19*(2), 600–606. https://doi.org/10.1007/s11356-011-0579-0

Davison, P., & Asch, R. G. (2011). Plastic ingestion by mesopelagic fishes in the North Pacific Subtropical Gyre. *Marine Ecology Progress Series*, *432*, 173–180. https://doi.org/10.3354/meps09142

Derraik, J. G. B. (2002). The pollution of the marine environment by plastic debris: a review. *Marine Pollution Bulletin*, *44*(9), 842–852. https://doi.org/10.1016/S0025-326X(02)00220-5

Evans, R. K. (1983). Selecting and testing heavy-duty synthetic ropes. *Materials and Design*, *4*(5), 885–888. https://doi.org/10.1016/0261-3069(83)90088-2

FAO. (2019). *Microplastics in fisheries and aquaculture: What do we know? Should we be worried?* Rome, Italy: Food and Agriculture Organization of the United Nations.

Fisheries and Oceans Canada. (2018). Plastics Challenge - Sustainable Fishing and Aquaculture Gear. Retrieved from https://www.ic.gc.ca/eic/site/101.nsf/eng/00037.html

Fisheries and Oceans Canada. (2019). Capelin Newfoundland & Labrador Region 2+3 (Capelin Fishing Areas 1-11). Retrieved August 21, 2019, from https://www.dfo-mpo.gc.ca/fisheries-peches/ifmp-gmp/capelin-area1-11-zone-capelan/capelin-capelan-2018-eng.html

Flory, J., Huntley, E., Richards, D., & Foster, G. (2004). Cordage Institute Rope Test Methods, Standards, and Guidelines. In *Ocean '04 - MTS/IEEE Techno-Ocean '04 - Conference Proceedings* (pp. 1887–1894). Institute of Electrical and Electronics Engineers.

Foekema, E. M., De Gruijter, C., Mergia, M. T., Van Franeker, J. A., Murk, A. J., & Koelmans, A. A. (2013). Plastic in north sea fish. *Environmental Science and Technology*, *47*(15), 8818–8824. https://doi.org/10.1021/es400931b

GESAMP. (2019). *Guidelines for the monitoring and assessment of plastic litter in the ocean*. (P. Kershaw, A. Turra, & F. Galgani, Eds.), *IMO/FAO/UNESCO-IOC/UNIDO/WMO/IAEA/UN/UNEP/ISA Joint Group of Experts on the Scientific Aspects of Marine Environmental Protection.* Retrieved from http://www.gesamp.org/publications/guidelines-for-the-monitoring-and-assessment-of-plastic-litter-in-the-ocean

Geyer, R., Jambeck, J., & Law, K. (2017). Production, use, and fate of all plastics ever made. *Science Advances*, *3*(7), 25–29. https://doi.org/https://doi.org/10.1126/sciadv.1700782

Goh, P. S., Ismail, A. F., & Ng, B. C. (2017). Raman Spectroscopy. In *Membrane Characterization* (Vol. 2, pp. 31–46). Elsevier. https://doi.org/https://doi.org/10.1016/B978-0-444-63776-5.00002-4

Goodman, A. J., Walker, T. R., Brown, C. J., Wilson, B. R., Gazzola, V., & Sameoto, J. A. (2020). Benthic marine debris in the Bay of Fundy, eastern Canada: Spatial distribution and categorization using seafloor video footage. *Marine Pollution Bulletin, 150*, 110722. https://doi.org/10.1016/j.marpolbul.2019.110722

Gregory, M. R. (1991). The hazards of persistent marine pollution: drift plastics and conservation islands. *Journal of the Royal Society of New Zealand*, *21*(2), 83–100. https://doi.org/10.1080/03036758.1991.10431398

Gregory, M. R. (2009). Environmental implications of plastic debris in marine settings—entanglement, ingestion, smothering, hangers-on, hitch-hiking and alien invasions. *Philosophical Transactions of the Royal Society B: Biological Sciences*, *364*(1526), 2013–2025. https://doi.org/10.1098/rstb.2008.0265

Grimaldo, E., Herrmann, B., Su, B., Føre, H. M., Vollstad, J., Olsen, L., … Tatone, I. (2019). Comparison of fishing efficiency between biodegradable gillnets and conventional nylon gillnets. *Fisheries Research*, *213*, 67–74. https://doi.org/10.1016/j.fishres.2019.01.003

ISO. (2006). *Fishing nets — Determination of breaking force and knot breaking force of netting yarns*. *(Standard No. 1805)*. Retrieved from https://www.iso.org/standard/30041.html

Khare, A., & Deshmukh, S. (2006). Studies toward producing eco-friendly plastics. *Journal of Plastic Film and Sheeting*, *22*(3), 193–211. https://doi.org/10.1177/8756087906067324

Kooi, M., Reisser, J., Slat, B., Ferrari, F. F., Schmid, M. S., Cunsolo, S., … Koelmans, A. A. (2016). The effect of particle properties on the depth profile of buoyant plastics in the ocean. *Scientific Reports*, *6*, 1–10. https://doi.org/10.1038/srep33882

Laist, D. W. (1997). Impacts of marine debris: entanglement of marine life in marine debris including a comprehensive list of species with entanglement and ingestion records. In *Marine Debris* (pp. 99–139). New York, NY: Springer. https://doi.org/10.1007/978-1-4613-8486-1_10

Lenz, R., Enders, K., Stedmon, C. A., MacKenzie, D. M. A., & Nielsen, T. G. (2015). A critical assessment of visual identification of marine microplastic using Raman spectroscopy for analysis improvement. *Marine Pollution Bulletin*, *100*(1), 82–91. https://doi.org/10.1016/j.marpolbul.2015.09.026

Liboiron, F., Ammendolia, J., Saturno, J., Melvin, J., Zahara, A., Richárd, N., & Liboiron, M.

(2018). A zero percent plastic ingestion rate by silver hake (Merluccius bilinearis) from the south coast of Newfoundland, Canada. *Marine Pollution Bulletin*, *131*, 267–275. https://doi.org/10.1016/j.marpolbul.2018.04.007

Liboiron, M., Charron, L., Duman, N., Melvin, J., Novacefski, M., Dawe, N., … Liboiron, F. (n.d.). *State of knowledge on plastic pollution in Newfoundland and Labrador*. St. John's, NL, Canada.

Liboiron, M., Liboiron, F., Wells, E., Richárd, N., Zahara, A., Mather, C., … Murichi, J. (2016). Low plastic ingestion rate in Atlantic cod (Gadus morhua) from Newfoundland destined for human consumption collected through citizen science methods. *Marine Pollution Bulletin*, *113*(1–2), 428–437. https://doi.org/10.1016/j.marpolbul.2016.10.043

Liboiron, M., Melvin, J., Richárd, N., Saturno, J., Ammendolia, J., Liboiron, F., … Mather, C. (2019). Low incidence of plastic ingestion among three fish species significant for human consumption on the island of Newfoundland, Canada. *Marine Pollution Bulletin*, *141*(2019), 244–248. https://doi.org/10.1016/j.marpolbul.2019.02.057

Logan, M. (2011). *Biostatistical Design and Analysis Using R: a practical guide*. West Sussex, UK: John Wiley & Sons.

Macfadyen, G., Huntington, T., & Cappell, R. (2009). *Abandoned, lost or otherwise discarded fishing gear*. *FAO Fisheries and Aquaculture Technical Paper 523*. Rome, Italy: FAO and UNEP. https://doi.org/10.1007/s10681-011-0422-1

Markic, A., Gaertner, J. C., Gaertner-Mazouni, N., & Koelmans, A. A. (2019). Plastic ingestion by marine fish in the wild. *Critical Reviews in Environmental Science and Technology*, 1–41. https://doi.org/10.1080/10643389.2019.1631990

Martinussen, A. O. (2007). Nylon fever: technological innovation, diffusion and control in

Norwegian fisheries during the 1950s., *5*(1), 29–44.

McCay, B. J. (1978). Systems ecology, people ecology, and the anthropology of fishing communities. *Human Ecology*, *6*(4), 397–422.

McWilliams, M., Liboiron, M., & Wiersma, Y. (2018). Rocky shoreline protocols miss microplastics in marine debris surveys (Fogo Island, Newfoundland and Labrador). *Marine Pollution Bulletin*, *129*(2), 480–486. https://doi.org/10.1016/j.marpolbul.2017.10.018

Meikle, J. L. (1997). Material Doubts: The Consequences of Plastic. *Environmental History*, *2*(3), 278–300.

Meintzer, P., Walsh, P., & Favaro, B. (2018). Comparing catch efficiency of five models of pot for use in a Newfoundland and Labrador cod fishery. *PLoS ONE*, *13*(6), 1–19. https://doi.org/10.1371/journal.pone.0199702

Melvin, J. (2017). *Plastic ingestion in Atlantic cod (Gadus morhua) on the east coast of Newfoundland, Canada: results from a citizen science monitoring project, with policy recommendations for long-term monitoring (Masters thesis)*. University of Akureyri. Retrieved from http://hdl.handle.net/1946/28666

Mengo, E. (2017). *A Review of Marine Litter Management Practices for the Fishing Industry in the North-East Atlantic Area*. Centre for Environment Fisheries and Aquaculture Science.

Moe, H., Dempster, T., Sunde, L. M., Winther, U., & Fredheim, A. (2007). Technological solutions and operational measures to prevent escapes of Atlantic cod (Gadus morhua) from sea cages. *Aquaculture Research*, *38*(1), 91–99. https://doi.org/10.1111/j.1365-2109.2006.01638.x

Niaounakis, M. (2017). The Problem of Marine Plastic Debris. In *Prevention, Recycling and Waste Management* (pp. 1–55). Elsevier. https://doi.org/https://doi.org/10.1016/B978-0-

323-44354-8.00001-X

NL Fisheries and Land Resources. (2018). *Seafood Industry: Year in Review*. St.John's, NL, Canada. Retrieved from https://www.fishaq.gov.nl.ca/publications/pdf/SYIR_2018.pdf

Noel, O. F., & Carley, J. F. (1975). Properties of Polypropylene-Polyethylene Blends. *Polymer Engineering and Science*, *15*(2).

Opara, U. L., & Mditshwa, A. (2013). A review on the role of packaging in securing food system: Adding value to food products and reducing losses and waste. *African Journal of Agricultural Research*, *8*(22), 2621–2630. https://doi.org/10.5897/AJAR2013.6931

Oxvig, U., & Jes Hansen, U. (2007). *Fishing gears* (2nd ed.). Fiskericirklen. Retrieved from http://www.fisheriescircle.com/Home/Educational+materials/Educational+materials/Fishing+gears

Pejakovi, V., Jisa, R., & Franek, F. (2015). Abrasion Resistance of Selected Commercially Available Polymer Materials. *Tribologia-Finnish Journal of Tribology*, *33*(1), 21–27.

Pivnenko, K., Jakobsen, L. G., Eriksen, M. K., Damgaard, A., & Astrup, T. F. (2015). Challenges in plastics recycling. In *Sardinia 2015-15th International Waste Management and Landfill Symposium*. CISA Publisher.

Provencher, J.F., Ammendolia, J., Rochman, C. M., & Mallory, M. L. (2018). Assessing plastic debris in aquatic food webs: what we know and don't know about uptake and trophic transfer. *Environmental Reviews*, *27*(3), 304–317. https://doi.org/10.1139/er-2018-0079

Provencher, Jennifer F., Gaston, A. J., Mallory, M. L., O'hara, P. D., & Gilchrist, H. G. (2010). Ingested plastic in a diving seabird, the thick-billed murre (Uria lomvia), in the eastern Canadian Arctic. *Marine Pollution Bulletin*, *60*(9), 1406–1411. https://doi.org/10.1016/j.marpolbul.2010.05.017

R Development Core Team. (2018). R: A language and environment for statistical computing. Vienna, Austria: R Foundation for Statistical Computing. Retrieved from http://www.r-project.org/

Radhalekshmy, K., & Nayar, S. G. (1973). Synthetic fibres for fishing gear. *Fishery Technology*, *10*(2), 142–165.

Ramos, J. A. A., Barletta, M., & Costa, M. F. (2012). Ingestion of nylon threads by gerreidae while using a tropical estuary as foraging grounds. *Aquatic Biology*, *17*(1), 29–34. https://doi.org/10.3354/ab00461

Reiss, C., McLaren, I., Avendaño, P., & Taggart, C. (2005). Feeding ecology of silver hake larvae on the Western Bank, Scotian Shelf, and comparison with Atlantic Cod. *Journal of Fish Biology*, *66*(3), 703–720. https://doi.org/10.1111/j.0022-1112.2005.00631.x

Richardson, K., Hardesty, B. D., & Wilcox, C. (2019). Estimates of fishing gear loss rates at a global scale : A literature review and meta - analysis. *Fish and Fisheries*, *20*(6), 1218–1231. https://doi.org/10.1111/faf.12407

Rochman, C. M., Brookson, C., Bikker, J., Djuric, N., Earn, A., Bucci, K., … Hung, C. (2019). Rethinking microplastics as a diverse contaminant suite. *Environmental Toxicology and Chemistry*, *38*(4), 703–711. https://doi.org/10.1002/etc.4371

Rochman, C. M., Browne, M. A., Halpern, B. S., Hentschel, B. T., Hoh, E., Karapanagioti, H. K., … Thompson, R. C. (2013). Comment: Classify plastic waste as hazardous. *Nature*, *494*(7436), 169–170. https://doi.org/10.1038/494169a

Rochman, C. M., Hoh, E., Kurobe, T., & Teh, S. J. (2013). Ingested plastic transfers hazardous chemicals to fish and induces hepatic stress. *Scientific Reports*, *3*, 1–7. https://doi.org/10.1038/srep03263

Rochman, C. M., Teh, S. J., Tahir, A., Teh, F.-C., Williams, S. L., Werorilangi, S., … Baxa, D. V. (2015). Anthropogenic debris in seafood: Plastic debris and fibers from textiles in fish and bivalves sold for human consumption. *Scientific Reports*, *5*(1), 14340. https://doi.org/10.1038/srep14340

Rummel, C. D., Löder, M. G. J., Fricke, N. F., Lang, T., Griebeler, E., Janke, M., & Gerdts, G. (2016). Plastic ingestion by pelagic and demersal fi sh from the North Sea and Baltic Sea. *Marine Pollution Bulletin*, *102*(1), 134–141. https://doi.org/10.1016/j.marpolbul.2015.11.043

Ryberg, M. W., Laurent, A., & Hauschild, M. (2018). *Mapping of global plastics value chain and plastics losses to the environment: With a particular focus on marine environment*. *UNEP*.

Salter, K. C., & Fawcett, R. F. (1993). The art test of interaction: A robust and powerful rank test of interaction in factorial models. *Communications in Statistics - Simulation and Computation*, *22*(1), 137–153. https://doi.org/10.1080/03610919308813085

Saturno, J., Liboiron, M., Ammendolia, J., Healey, N., Earles, E., Duman, N., … Favaro, B. (2020). Occurrence of plastics ingested by Atlantic cod (Gadus morhua) destined for human consumption (Fogo Island, Newfoundland and Labrador). *Marine Pollution Bulletin*, *153*, 110993. https://doi.org/10.1016/j.marpolbul.2020.110993

Seo, M., wu, H. C., Chen, J., Toomey, C. S., & Backer, S. (1997). Wear and Fatigue of Nylon and Polyester Mooring Lines. *Textile Research Journal*, *67*(7), 467–480. https://doi.org/10.1177/004051759706700701

Sigler, M. (2014). The effects of plastic pollution on aquatic wildlife: Current situations and future solutions. *Water, Air, and Soil Pollution*, *225*(11). https://doi.org/10.1007/s11270-

014-2184-6

Singh, B., & Sharma, N. (2008). Mechanistic implications of plastic degradation. *Polymer Degradation and Stability*, *93*(3), 561–584. https://doi.org/10.1016/j.polymdegradstab.2007.11.008

Song, Y. K., Hong, S. H., Jang, M., Myung, G., Rani, M., Lee, J., & Joon, W. (2015). A comparison of microscopic and spectroscopic identification methods for analysis of microplastics in environmental samples. *Marine Pollution Bulletin*, *93*(1–2), 202–209. https://doi.org/10.1016/j.marpolbul.2015.01.015

Sussarellu, R., Suquet, M., Thomas, Y., Lambert, C., Fabioux, C., Pernet, M. E. J., … Huvet, A. (2016). Oyster reproduction is affected by exposure to polystyrene microplastics. *Proceedings of the National Academy of Sciences*, *113*(9), 2430–2435. https://doi.org/10.1073/pnas.1519019113

Suuronen, P., Chopin, F., Glass, C., Løkkeborg, S., Matsushita, Y., Queirolo, D., & Rihan, D. (2012). Low impact and fuel efficient fishing-Looking beyond the horizon. *Fisheries Research*, *119–120*, 135–146. https://doi.org/10.1016/j.fishres.2011.12.009

Teuten, E. L., Saquing, J. M., Knappe, D. R. U., Barlaz, M. A., Jonsson, S., Björn, A., … Takada, H. (2009). Transport and release of chemicals from plastics to the environment and to wildlife. *Philosophical Transactions of the Royal Society B: Biological Sciences*, *364*(1526), 2027–2045. https://doi.org/10.1098/rstb.2008.0284

Thompson, R. C., Swan, S. H., Moore, C. J., & Vom Saal, F. S. (2009). Our plastic age. *Philosophical Transactions of the Royal Society B: Biological Sciences*, *364*(1526), 1973–1976. https://doi.org/10.1098/rstb.2009.0054

Torre, M., Digka, N., Anastasopoulou, A., Tsangaris, C., & Mytilineou, C. (2016).

Anthropogenic microfibres pollution in marine biota. A new and simple methodology to minimize airborne contamination. *Marine Pollution Bulletin*, *113*(1–2), 55–61. https://doi.org/10.1016/j.marpolbul.2016.07.050

Tóth, S., Füle, M., Veres, M., Pócsik, I., Koós, M., Tóth, A., … Bertóti, I. (2006). Photoluminescence of ultra-high molecular weight polyethylene modified by fast atom bombardment. *Thin Solid Films*, *497*(1–2), 279–283. https://doi.org/10.1016/j.tsf.2005.10.050

UNEP. (2014). *UNEP Year Book 2014 emerging issues update*. Nairobi, Kenya: United Nations Environment Programme. https://doi.org/doi.org/10.1016/j.envpol.2014.06.010

Van Cauwenberghe, L., & Janssen, C. R. (2014). Microplastics in bivalves cultured for human consumption. *Environmental Pollution*, *193*, 65–70. https://doi.org/10.1016/j.envpol.2014.06.010

Walker, T. R., Reid, K., Arnould, J. P. Y., & Croxall, J. P. (1997). Marine debris surveys at Bird Island, South Georgia 1990-1995. *Marine Pollution Bulletin*, *34*(1), 61–65. https://doi.org/10.1016/S0025-326X(96)00053-7

Walsh, P., Hiscock, W., & Sullivan, R. (2005). *Fishing For Atlantic cod (Gadus morhua) using experimental baited pots*. St. John’s, NL, Canada: Fisheries & Marine Institute of Memorial University of Newfoundland.

Welden, N. A. C., & Cowie, P. R. (2016). Long-term microplastic retention causes reduced body condition in the langoustine, Nephrops norvegicus. *Environmental Pollution*, *218*, 895–900. https://doi.org/10.1016/j.envpol.2016.08.020

Welden, N. A., & Cowie, P. R. (2017). Degradation of common polymer ropes in a sublittoral marine environment. *Marine Pollution Bulletin*, *118*(1–2), 248–253.

https://doi.org/10.1016/j.marpolbul.2017.02.072

Weller, S., Davies, P., Johanning, L., & Banfield, S. (2013). *Guidance on the use of synthetic fibre ropes for marine energy devices. University of Exeter*.

Wobbrock, J. O., Findlater, L., Gergle, D., & Higgins, J. J. (2011). The Aligned Rank Transform for nonparametric factorial analyses using only ANOVA procedures. In *Proceedings of the SIGCHI conference on human factors in computing systems* (pp. 143–146). https://doi.org/10.1145/1978942.1978963

Zuur, A. F., Ieno, E. N., & Meesters, E. H. W. . (2009). *A Beginner's Guide to R*. *Applied Spatial Data Analysis with R*. Springer Science & Business Media. https://doi.org/10.1007/978-0-387-78171-6