A COMPARISON OF MICROPLASTICS EFFECTS ON ATLANTIC COD (*Gadus morhua*) AND BLUE MUSSELS (*Mytilus edulis*)

by

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ABSTRACT

Bailey, K. 2020. A Comparison Microplastics Effects on Atlantic Cod (*Gadus morhua*) and Blue Mussels (*Mytilus edulis*). 54 pp.

Key Words: Atlantic cod, blue mussels, microplastics, potential effects, contaminant, species function

This thesis explores the potential impacts that can occur in Atlantic cod and blue mussels resulting from the ingestion of microplastic particles based on a review of previously published studies. This thesis summarizes the differing lifestyles and feeding strategies of both species and how these features are either beneficial or unfavourable with respect to the ingestion of microplastics. The is review identified a total of twenty potential effects were found to occur in both species when they were exposed to microplastics. Twelve of the effects were shared between Atlantic cod and blue mussels; however, overall observed responses varied between the two species. Results showed that blue mussels seem to face a greater exposure to microplastics than Atlantic cod. The type and severity of effects were found to differ depending upon the amount of particles ingested and the duration of exposure. As this is a somewhat new area of research much information remains unknown. This is especially true in the case of Atlantic cod as there is much less data and completed studies compared to those which is available for blue mussels.

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INTRODUCTION

Since industrial manufacturing of plastics began in the early 1950s their popularity has steadily increased, which has lead to a global increase in plastic production. In 2018 the world produced 359 million tonnes of plastic, which is up from the 348 million tonnes produced in 2017 (Plastics Europe 2019), and 335 million tonnes from 2016 (Plastics Europe 2018). As the production continues to rise, the issue of plastic pollution will continue to rise as well.

Plastic is a synthetic material made from organic polymers whose physical and chemical properties can fluctuate to produce versatile products with varying durability and environmental impacts (Au 2017). The plastic industry is prevalent in almost all societal sectors including building and construction, automotive, packaging, electronics, agriculture, and household objects (Plastics Europe 2018). Of these, packaging is the most demanding sector accounting for 39.7 percent of total plastic usage (Plastics Europe 2019). Most plastic waste takes a very long time to decompose and can remain in the environment for hundreds of years. An estimated ten percent of this waste ends up in the ocean (Blair et al. 2017). As this accounts to an estimated 8 million tonnes of plastic entering the ocean each year, it has become a significant element in the marine ecosystem (Anderson 2019).

A microplastic is defined as a plastic item that is no more than 5 millimetres at its longest point, and nanoplastics, which are plastics measuring less than 100 nanometers, are also encompassed under this term (Lusher et al. 2017). Microplastics can either result from the direct production of particles of this size, known as primary microplastics, or from the breakdown of larger plastic products, which are classified as secondary microplastics (Carlos de Sá et al. 2018). Primary microplastics include fragments, fibers, industrial pellets, and microbeads found in health and beauty products (Au 2017, Carlos de Sá et al. 2018). The majority of microplastics found in the environment are secondary microplastics (Au 2017).

The Atlantic cod (*Gadus morhua*) and blue mussel (*Mytilus edulis*) were specifically selected for their ability to complement each other. The two species represent two vastly different lifestyles and feeding strategies. Also, together they consume a wide variety of shapes, types, and sizes of microplastic particles (Hantoro et al. 2019). This exhibits the wide range of particles that potentially pose a threat to marine organisms.

The range of Atlantic cod extends from Greenland to Cape Hatteras, North Carolina (NOAA Fisheries 2019). Throughout history in Atlantic Canada, it has been a species of cultural and economic significance (Melvin 2017). Even after the collapse of the cod fishery, it remains an important food source (Melvin 2017).

The diet of Atlantic cod changes throughout their life cycle. Larvae feed upon plankton in the upper water column, then their diet changes to increasingly larger prey as they grow throughout their juvenile and adult stages (Oceana 2019).

Blue mussels (*Mytilus edulis*) are found throughout the Arctic Ocean, North Pacific Ocean, and North Atlantic Ocean (Newell 1989), and in the western North Atlantic their range extends from Labrador to South Carolina (Fisheries and Oceans Canada 2003). They are an important member of the Canadian aquaculture industry accounting for half of the shellfish production in the country (Nguyen and Williams 2013). Blue mussels are filter-feeding bivalves, and the majority of their diet consists of phytoplankton (NOAA Fisheries 2015).

The size and makeup of plastic particles influences the ways it effects a species (Lusher 2015). For example, Atlantic cod can ingest larger particles than the selective feeding blue mussels, meaning particles too large to be ingested by the mussel can still affect cod (Rist et al. 2018). Blue mussels generally intake plastic particles during filter feeding and they can remain in their system for upwards of 48 days (Browne et al. 2008), while Atlantic cod most commonly ingest particles directly (Lusher 2015), and only remain in their system for up to four days (Brate et al. 2016)

OBJECTIVE

The purpose of this thesis is to investigate past studies that have looked at the presence of microplastics in the Atlantic Ocean and how they impact two marine species of varying feeding strategies and lifestyles, Atlantic cod and blue mussels. This thesis will investigate the ways in which microplastics impact the natural history and health of both species. It will also investigate the potential risks to the two species. It is worth noting that the study of microplastics is relatively new and is a growing problem that the world is facing.

HYPOTHESIS

The following is the null hypothesis (Ho) for this thesis: Differences in the natural history and physiology of the Atlantic cod (*Gadus morhua*) and blue mussel (*Mytilus edulis*) will not induce varied interactions with microplastic particles and therefore will not result in an observed difference in the type, or severity, of effects caused by microplastic ingestion.

LITERATURE REVIEW

Atlantic Cod (*Gadus morhua*)

Species traits

Atlantic cod are found in the northwest and northeast continental shelf waters of the Atlantic Ocean. Their range extends from Cape Hatteras, North Carolina in the southern portion of the population, around Newfoundland and Labrador to Baffin Island in the north, and to the western coast of Greenland (COSEWIC 2010, NOAA Fisheries 2019). There are six identified populations of Atlantic cod in Canada, which are based upon geographical area of occurrence (Figure 1). These include the Laurentian North population, Laurentian South population, Newfoundland and Labrador population, Southern population, Arctic Lakes population, and the Arctic Marine population. Of the six populations, four are designated as endangered. The two that are not are the Arctic Lakes population which is of special concern, and the Arctic Marine population which has insufficient data (COSEWIC 2010).

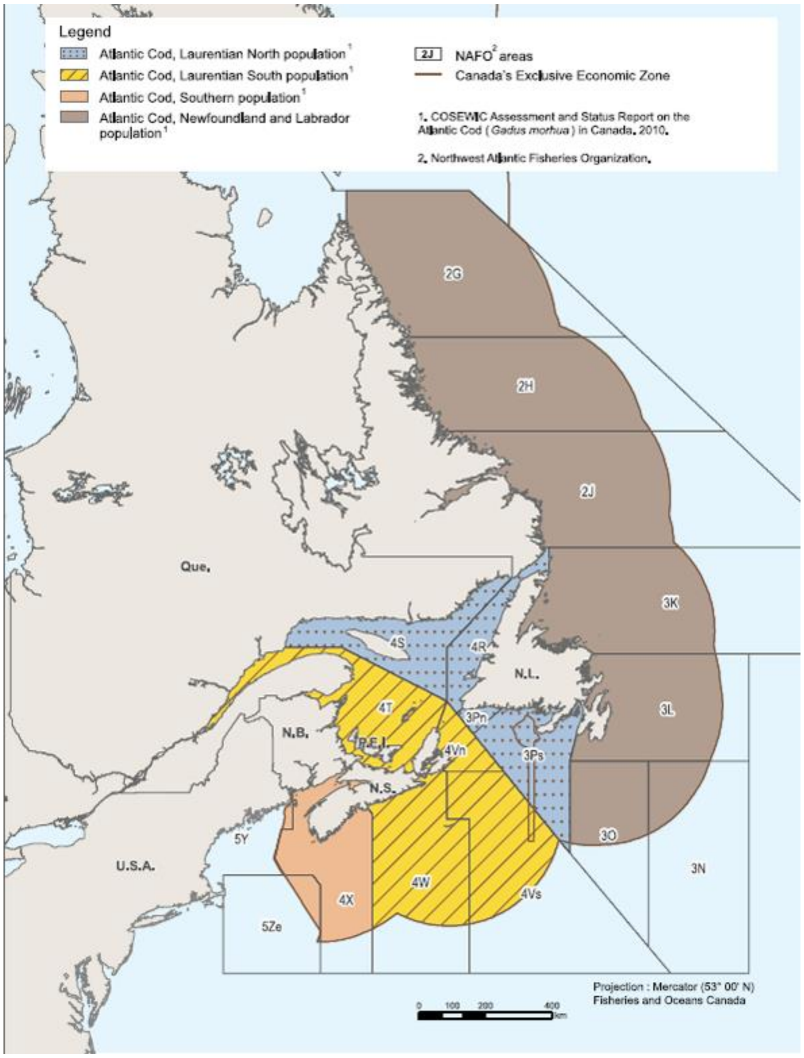

Figure 1. Geographical ranges of four of the Canadian Atlantic cod populations (Source: GOC Species at Risk Public Registry).

Atlantic cod have a streamlined body shape, an apparent lateral line, colour ranges varying from yellowish green to red to olive brown, and have three distinct dorsal fins (Figure 2) (NOAA Fisheries 2019, Oceana 2019). They exhibit broadcast spawning, as depending on size, they release between 300 000 and 9 million buoyant eggs. The eggs are released over a three to six week period in the upper water column then are later fertilized (COSEWIC 2010, Grabowski et al. 2012, Oceana 2019). Individuals reach sexual maturity anywhere from two to seven years of age, with individuals in more southern ranges tending to mature faster than those in northern areas (COSEWIC 2010, Oceana 2019).

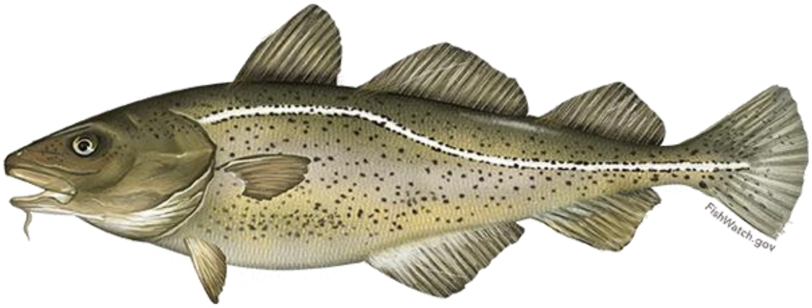

Figure 2. Illustration of an adult Atlantic cod (Source: NOAA Fisheries).

Habitat and Life Stages

Atlantic cod are a migratory species that associate with a variety of habitats throughout their lifetime (Cote et al. 2004, Grabowski et al. 2018, Guan et al. 2017). During the egg and larval stages, they are found in the upper 50 meters of the water column. They select areas with high food availability consisting of large amounts of phytoplankton and zooplankton, and can retain their eggs without dispersing them (COSEWIC 2010, Oceana 2019). Once in the juvenile stage, which is from the first one to four years of life, the cod move to the lower water column in varying depths between less than ten meters to 150 meters (COSEWIC 2010). They tend to select habitats of structural complexity, which most often consist of pebbled or cobbled substrates that contain eelgrass or other seagrass beds that offer protection from predators (COSEWIC 2010, Cote et al. 2004, Lilley and Unsworth 2014, Grabowski et al.

2018, Oceana 2019). Eelgrass meadows are a habitat of high value for young cod and have even been associated with increased survival and likelihood of reaching adulthood (Grabowski et al. 2018, Lilley and Unsworth 2014). Throughout the juvenile stage of their life, their diet consists of small crustaceans such as shrimp and krill (COSEWIC 2010, Oceana 2019). During adulthood, Atlantic cod are far less selective as they inhabit a diverse range of areas (Guan et al. 2017), which tend to be selected upon based on temperature and food supply (COSEWIC 2010). Adult Atlantic cod reach upwards of 100cm in length and are one of the top predators in the lower ocean. They feed upon a number of invertebrates and fish (COSEWIC 2010, NOAA Fisheries 2019, Oceana 2019), namely Atlantic herring (*Clupea herengus*) and capelin (*Mallotus villosus*) (Canadian Museum of Nature 2015).

Significance to Humans

Atlantic cod are considered one of the most iconic species in Canada (COSEWIC 2010, Oceana 2019). This is because they have had such a significant historical, cultural, and economic value in Atlantic Canada, especially Newfoundland (COSEWIC 2010, Cote et al. 2004, Oceana 2019). From the 1950s to the 1970s, they were found in very high abundance in Atlantic Canada and were the most important fishery in the country (Oceana 2019). This was the case until the species suffered a massive population decline, which has been attributed to intense overfishing, that led to the collapse of the Atlantic cod fishery in the early 1990s (Cote et al. 2004, Guan et al. 2017, Oceana 2019). Yet, commercial marine fishing remains a major industry on the east coast of Canada, especially in the provinces of Nova Scotia and Newfoundland and Labrador (Table 1) (Cote et al. 2004, Fisheries and Oceans Canada 2016). In 2008 alone, the landing value of Atlantic cod totalled $677 million in Nova Scotia and $530 million in Newfoundland and Labrador. Of all the active marine fishing vessels in Canada in 2008, thirty percent targeted Atlantic cod (Fisheries and Oceans Canada 2016).

Table 1. Total landed value of Canadian provinces by commercial marine fisheries in 2008 (Source: Fisheries and Oceans Canada 2016).

Province	Total landed value ($ million)
Nova Scotia	677
Newfoundland and Labrador	530
British Columbia	247
New Brunswick	170
Quebec	142
PEI	124

Atlantic cod remains an economically important species in the Canadian fishing industry, even after the collapse of the cod fishery (COSEWIC 2010, Fisheries and Oceans Canada 2016, Oceana 2019). However, there are now restrictions and safeguards put in place to manage and promote the recovery of the population. The *Fisheries Act* and the *Oceans Act* protect Atlantic cod in Canada, and Conservation Harvesting Plans have been set in the Gulf of St. Lawrence. Also, Newfoundland, the Maritimes, and Quebec each have Cod Action Teams whose goal is to recover the species popuations (COSEWIC 2010). These protective measures have been established in hopes of avoiding another collapse or loss of this iconic Canadian species.

Blue Mussel (*Mytilus edulis*)

Species Traits

The blue mussel (*Mytilus edulis*) is found throughout the Arctic Ocean, the North Pacific, and the North and Mid-Atlantic Ocean (Fisheries and Oceans Canada 2003, Newell 1989, NOAA Fisheries 2015, McGill University Department of Geography n.d., Picoche et al. 2014). They range from Labrador to South Carolina in the western North Atlantic (Fisheries and Oceans Canada 2003, Newell 1989, NOAA Fisheries 2015, McGill University Department of Geography n.d., Safina Center and Monterey Bay Aquarium 2019). The limit of their northern range is established by their need for temperatures above 5 degrees Celsius for a long enough time period to promote growth and reproduction (McGill University Department of Geography n.d., Newell 1989). The blue mussel occurs in the same area as the closely related bay mussel (*Mytilus trossulus)* and occurrences of hybridization have been noted between the two species (McGill University Department of Geography n.d.).

The adult shell of the blue mussel is an elongate triangle in shape measuring between seven and ten centimeters at the longest point (Figure 3) (Newell 1989, Safina Center and Monterey Bay Aquarium 2019). The outer adult shell is covered in a shiny, protective membrane, termed the periostracum, and is most often blue to black, but can sometimes be brownish in colour (Figure 3). The inside of the shell is white or violet with a violet to dark blue border (Fisheries and Oceans Canada 2003, Newell 1989). Some major features of the internal anatomy of the mussel include the visceral mass, heart, gills, stomach, mantle, foot, posterior and anterior adductor muscles, with the posterior being much larger (Figure 4) (Fisheries and Oceans Canada 2003, Newell 1989). Byssal threads, which are fibers that function in anchoring the individual, are secreted by the foot (Fisheries and Oceans Canada 2003, Newell 1989, McGill University Department of Geography n.d.).

Figure 3. Outer shell of adult blue mussel (Source: University of Alaska Geophysical Institute).

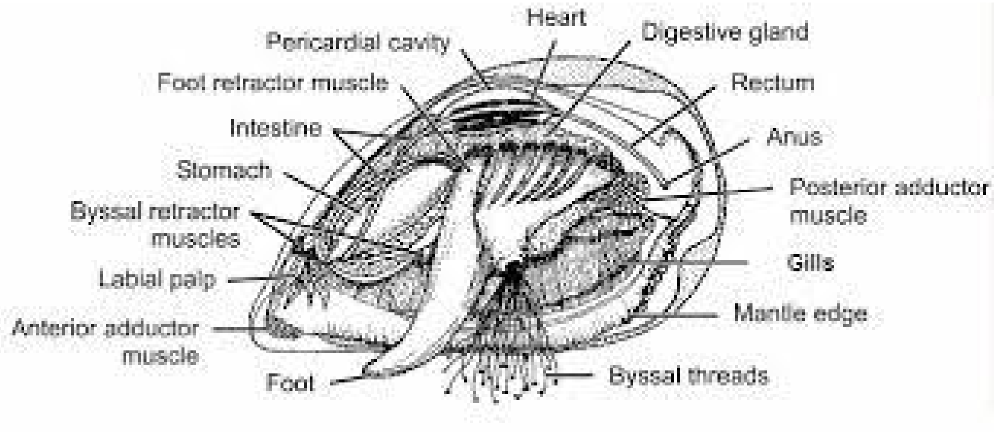

Figure 4. Major internal anatomical features of the blue mussel (Source: Fisheries and Oceans Canada).

Habitat and Life Stages

The blue mussel is a semi-sessile member of the bivalve class (Fisheries and Oceans Canada 2003, Newell 1989, NOAA Fisheries 2015, McGill University Department of Geography n.d., Safina Center and Monterey Bay Aquarium 2019). They can tolerate a wide range of conditions, including variations in temperature and salinity (FAO of the UN 2020, Fisheries and Oceans Canada 2003). Their preferred habitat is in areas of high nutrient runoff in bays and estuaries, which can exceed depths of 300 meters. Blue mussels can also be found in deep offshore waters (Fisheries and Oceans Canada 2003, Newell 1989, McGill University Department of Geography n.d.). Using their byssal threads, adults anchor themselves to the substrate or other mussels forming aggregations when space is limited (Newell 1989, McGill University Department of Geography n.d.). Most often, juveniles are found in littoral to sublittoral zones, which are less than 99 meters in depth. (Newell 1989, McGill University Department of Geography n.d.). Blue mussels exhibit filter feeding throughout their life (Newell 1989, McGill University Department of Geography n.d., Picoche et al. 2014), and feed upon organic particles mainly consisting of phytoplankton and sometimes bacteria (Newell 1989, NOAA Fisheries 2015).

Reproductive maturity is often reached at one year of age, however can be delayed to the second year if development occurs under poor conditions (Newell 1989, NOAA Fisheries 2015, Safina Center and Monterey Bay Aquarium 2019). The timing of reproductive events is dependent upon the availability of food and environmental conditions (Fisheries and Oceans Canada 2003, NOAA Fisheries 2015).

Males tend to be the first to release gametes, triggering females to then release their eggs (Newell 1989, NOAA Fisheries 2015). Although not all are fertilized, females produce thousands of eggs (NOAA Fisheries 2015). Fertilization occurs in the water column producing larvae. Individuals then remain in the larval stage for 15 to 35 days (Fisheries and Oceans Canada 2003, Newell 1989, McGill University Department of Geography n.d.). After the larval stage the mussels enter the juvenile stage, which can last up to two years before entering the adult stage. Blue mussels can live for up to 20 years (Fisheries and Oceans Canada 2003, Newell 1989). Growth occurs more rapidly under warmer conditions (Fisheries and Oceans Canada 2003, Newell 198), and is maximized between 16 degrees Celsius and 22 degrees Celsius (McGill University Department of Geography n.d.).

Significance to Humans

Blue mussels are a species of commercial significance and have been consumed by humans for centuries (FAO of the UN 2011, Fisheries and Oceans Canada 2003, NOAA Fisheries 2015, McGill University Department of Geography n.d., Picoche et al. 2014). In Canada, the blue mussel is second only to Atlantic salmon (*Salmo salar*) in terms of economic importance in the aquaculture industry. In 2011, blue mussels accounted for 17 percent of total industry production (FAO of the UN 2011), and half of total shellfish value (Nguyen and Williams 2013). With regards to the aquaculture industry and rural and coastal communities, they are an important contributor to the economy with total production values reaching 39 million CAD in 2013 (FAO of the UN

2011, Nguyen and Williams 2013). Blue mussels are fished or farmed in the Maritime provinces, Newfoundland and Labrador, Quebec, and British Columbia (Table 2) (Canadian Aquaculture Industry Alliance 2017, Canadian Aquaculture Industry Alliance 2018, FAO of the UN 2011, McGill University Department of Geography n.d., Nguyen and Williams 2013). Prince Edward Island is the main producer of the species accounting for over 55 percent of total production (Table 2) (Canadian Aquaculture Industry Alliance 2017, Canadian Aquaculture Industry Alliance 2018, FAO of the UN 2011, Nguyen and Williams 2013).

Table 2. Total shellfish production by province in 2011 (Source: Statistics Canada, Aquaculture Statistics 2011).

Province	Tonnes	% of Total
Newfoundland and Labrador	3000	7.7
PEI	23108	59.7
Nova Scotia	2199	5.7
New Brunswick	634	1.6
Quebec	394	1.0
British Columbia	9400	24.3
Total	39735	

Blue mussels provide further benefits to coastal ecosystems as they contribute to shoreline protection, provide habitat for a variety of species, and help to remove pollutants from the water (Browne et al. 2008, Safina Center and Monterey Bay Aquarium 2019). The aquaculture industry also continues to increase Indigenous involvement across Canada, providing opportunities for jobs and economic development for more than 40 First Nation and Indigenous communities involved in the industry (Canadian Aquaculture Industry Alliance 2017, FAO of the UN 2011, Fisheries and Oceans Canada 2003, Nguyen and Williams 2013).

Plastics

Demand

Due to the high versatility, light-weight, and durability of plastics, they have become essential in human society and their popularity has substantially grown since the industrial manufacturing of plastics began in the early 1950s (Almroth and Eggert 2019, Anderson 2019, d'Ambrières 2019, Plastics Europe 2018). The two categories of plastics are thermoplastics and thermosets. Thermoplastics can be repeatedly reheated and reshaped, while thermosets can only be melted and shaped once (Plastics Europe 2018, Plastics Europe 2019). In order to keep up with current demands, global production in 2018 reached 359 million tonnes, which increased from the 348 million tonnes produced in 2017 (Plastics Europe 2019), and the 335 million tonnes in 2016 (Plastics Europe 2018), making plastic one of the most common manmade materials, surpassed only by concrete and steel (Almroth and Eggert 2019). Worldwide, the plastic industry has become a vital part of many countries' economies as it provides a variety of jobs in many areas including raw materials producers, converters, recyclers, and machinery manufacturers (Plastics Europe 2018, Plastics Europe 2019). A great deal of society is highly dependent on plastics, so much so that it has replaced many traditional materials including glass, steel, wood, and concrete (d'Ambrières 2019). The sectors of society which are the most demanding are the packaging, building and construction, and automotive industries (Mason 2019, Plastics Europe 2018). The plastic polymers in heaviest demand are polypropylene, low, medium, and high-density polyethylene, and polyvinyl-chloride (Plastics Europe 2018, Plastics Europe 2019).

Disposal and the Environment

Plastic waste can be disposed of in a variety of ways including incineration, recycling, or placement into landfills (Almroth and Eggert 2019, Au 2017, Mason 2019). But only about 10 percent of the world's total plastic waste is recycled and about 60 percent ends up in landfills (Almroth and Eggert 2019, d'Ambrières 2019, Mason 2019). Canada's plastic recycling rate is similar to that of the world's, as only nine percent of the 3.3 million tonnes of plastics used by Canadians each year get recycled (Young 2019). This low rate of recycling is in large part due to the considerable sorting and processing infrastructure and accompanied regulations that are required to both fulfill and encourage the recycling process. Even in places such as Japan and Western Europe where this system exists, only about 30 percent of plastic waste is recycled (d'Ambrières 2019).

Each year an estimated ten million tonnes of plastic enters the natural environment, with over eight million tonnes of which landing in the ocean (Anderson 2019, d'Ambrières 2019, Kerscher 2019). The most common types of plastic litter in the ocean are polypropylene, polyethylene, polyvinylchloride, polyurethane, polyterephthalate, and polystyrene (Almroth and Eggert 2019, Au 2017, Carlos de sá et al. 2018, Guzzetti et al. 2018, Lusher et al. 2017). This plastic litter finds its way to the ocean in a variety of manners (Almroth and Eggert 2019, Guzzetti et al. 2018). Coastal land pollution, comprising areas within 50 km of the coastline, accounts for the largest source of ocean plastic pollution, followed by direct sea sources, then inland sources (Almroth and Eggert 2019). Ninety-four percent of the plastic that enters the ocean accumulates on the ocean floor, 5 percent lands on beaches, and the remaining 1 percent persists at the surface (Almroth and Eggert 2019).

Much of the plastic waste found in waterways are microplastics, which can either be initially produced as microplastics or result from weathering and fragmentation of larger pieces (Almroth and Eggert 2019, Carlos de Sá et al. 2018). Microplastics are not removed by wastewater treatment facilities and as such directly enter waterways after passing through them (Au 2017, Cheung et al. 2018, Mason 2019, Nelms et al. 2019, Walkinshaw et al 2020). Every day, a wastewater treatment facility in the United States is faced with an average of four million particles of microplastics, which occur in the form of fibers, beads, films, and foams (Kerscher 2019, Mason 2019). The source of these microplastics can range from laundry to microbeads that were previously found in many personal care products (Cheung et al. 2018, Mason 2019, Nelms et al. 2019). As of July 1, 2018, the Government of Canada has prohibited the manufacture and import of all toiletries that contain plastic microbeads, and many other countries have enforced similar measures (Government of Canada 2018). Furthermore, each article of clothing made from synthetic fibres such as polyester, nylon, and acrylic, all of which are forms of plastic, can release more than

1900 fibers during one wash (Au 2017). Once they have reached the natural environment it is infeasible, both practically and economically, to retain the microplastics for recycling or disposal (Walkinshaw et al. 2020).

Depending on the size of a plastic, it can be categorized as a mesoplastic (>5mm), or a microplastic (<5mm). Other size groupings include nanoplastics and macroplastics (Table 3) (Au 2017, Besseling et al. 2017, Blair et al. 2017, Carlos de sá et al. 2018, Lusher et al. 2017, Melvin 2017).

Table 3. Category of plastics based on diameter size (Au 2017).

Category	Diameter (mm)
Nanoplastic	<0.0001
Microplastic	0.0001 – 5
Mesoplastic	5.01 – 200
Macroplastic	>200

Microplastics can be further classified into two categories, primary and secondary, based on their source. Primary microplastics are those which are directly manufactured at sizes smaller than five mm (Au 2017, Blair et al. 2017, Carlos de sá et al. 2018, Cheung et al. 2018, Lusher et al. 2017) and can be found as microbeads in personal care products, cleaning products, and pellets for other goods (Blair et al. 2017, Lusher et al. 2017, Melvin 2017). Alternatively, the more common type of microplastic found in the environment is secondary microplastics, which result from the breakdown of larger plastic products (Au 2017, Blair et al. 2017, Carlos de sá et al. 2018, Cheung et al. 2018, Lusher et al. 2017). Fragmentation or breakdown can occur due to exposure to ultraviolet radiation, microorganisms, or physical breakdown from waves for example (Blair et al. 2017, Carlos de sá et al. 2018, Lusher et al. 2017, Melvin 2017). The origins of secondary microplastics are more difficult to trace than primary microplastics, thus making them harder to control (Blair et al. 2017). Depending on the makeup of a plastic, within a few weeks of release into the aquatic ecosystem breakdown can occur to form a microplastic (Au 2017). The rate of degradation and strength of a product is affected by the type of polymer it is created from as well as its crystallinity, which in turn affects the amount of microplastic particles produced by the product (Au 2017).

Methods of Uptake

The method of microplastic uptake by an organism is affected by its lifestyle, feeding habits, and physical structure (Au 2017, Bessa et al. 2017, Lusher 2015, Lusher et al. 2017, Walkinshaw et al. 2020). Microplastics can be consumed by a wide variety of aquatic species including protists, copeopods, annelids, echinoderms, cnidaria, amphipods, decapods, isopods, molluscs, fish, and birds (Au 2017, Lusher et al. 2017, Van Cauwenberghe et al. 2015, von Moos et al. 2012). Studies suggest that microplastics do not biomagnify, and many methods of uptake are possible, such as adherence, trophic transfer, direct consumption by suspension and deposit feeders, and ingestion (Lusher 2015, Lusher et al. 2017, Nelms et al. 2019, Walkinshaw et al. 2020).

Toxicity

Because microplastics have a range of physical properties, they have been detected in virtually all elements of the aquatic ecosystem including beach sediment, sea bottom sediments, the water surface, and throughout the water column (Almroth and Eggert 2019, Bessa et al. 2018, Cheung et al. 2018, Liboiron 2016, Lusher 2015, Lusher et al. 2017, Melvin 2017, Walkinshaw et al. 2020). Microplastics are highly resistant to degradation and as a result may linger in the ocean with the possibility of negatively effecting organisms for hundreds of years (Guzzetti et al. 2018). They can have varying impacts on species depending on their lifestyle and physical features, but generally tend to present a risk to marine life and associated ecological processes (Au 2017, Lusher et al. 2017, Walkinshaw et al. 2020).

The properties of the plastic particles, including polymer type, shape, and size, can also induce varied effects (Au 2017, Lusher 2015, Lusher et al. 2017). Multiple studies have observed that fibers are the most common shape ingested by most species (Cheung et al. 2018, Nelms et al. 2019, Walkinshaw et al. 2020).

Compared to apex predators, organisms occupying lower trophic levels are at greater risk of microplastic contamination, as they tend to contain higher concentrations of microplastics (Walkinshaw et al. 2020).

There are two categories of effects that microplastics potentially have on marine species. There are direct effects which consist of those to growth, reproduction, injuries, stress, and mortality, and indirect effects which consist of those resulting from the disruption of natural processes, carbon flux, and disruption of marine nutrient cycling, all of which have negative repercussions on ecosystem health (Guzzetti et al. 2018, Walkinshaw et al. 2020). In general, marine species have been found to suffer reduced growth rates, reproductive function, and behavioural changes when they encounter microplastics (Almroth and Eggert 2019, Bessa et al. 2018, Walkinshaw et al. 2020).

Microplastics have a large surface area compared to their volume and the surface of many particles is porous and rough (Peng et al. 2020). Due to this, marine plastics are highly adept to absorb and carry pollutants and pathogenic organisms (Peng et al. 2020, Walkinshaw et al. 2020). Notable pathogenic organisms microplastics in the North Atlantic are capable of supporting are those of the *Vibrio* and *Alexandrium* genera, which include species toxic to humans and animals (Walkinshaw et al. 2020). Because of this there is an increased risk of disease contraction by cod and blue mussels when ingesting these species (Cheung et al. 2018, Lusher et al. 2017, Melvin 2017, Nelms et al. 2019).

Chemical additives, which are added during the manufacturing stage, and can be absorbed once in the natural ecosystem are another toxic component of plastics with the potential to impair organisms (Almroth and Eggert 2019, Browne et al. 2008, Guzzetti et al. 2018, Mason 2019, Van Cauwenberghe et al. 2015). Flame-retardants, antimicrobials, and emollients are all examples of chemical additives, while environmental contaminants include pesticides, herbicides, heavy metals, and persistent organic pollutants (Guzzetti et al. 2018). These contaminated plastics have the potential to affect metabolic and reproductive function, lower immune system function, or increase stress of the organisms they come into contact with (Almroth and Eggert 2019, Guzzetti et al. 2018).

Atlantic Cod

The ingestion of microplastics by fish can occur if a predator mistakes plastic particles for prey, by secondary ingestion if a predator consumes an already contaminated prey, during filter feeding, or by choosing to feed on plastic particles that host microorganisms (Au 2017, Bassa et al. 2018, Carlos de sá et al. 2018, Guzzetti et al. 2018, Lusher 2015, Lusher et al. 2017, Melvin 2017, Walkinshaw et al. 2020). Although Atlantic cod occupy a variety of habitats throughout their life cycle, once they reach maturity, which is usually after four years of age (COSEWIC 2010, Grabowski et al. 2018, Oceana 2019), they inhabit the areas below pelagic waters but above the ocean floor, knows as benthopelagic zones (Liboiron 2016). This may make them less likely to come into contact with low density plastics found in the upper water column, and high-density plastics that occur on the ocean floor (Choy et al. 2019, Liboiron 2016). However, they have still been noted to ingest microplastics directly or through secondary ingestion of contaminated prey (Bessa et al. 2018, Liboiron 2016, Melvin 2017).

Microplastics have been noted to cause negative effects when ingested by marine fish, such as Atlantic cod (Almroth and Eggert 2019, Anbumani and Kakkar 2018, Anderson et al. 2016, Au 2017, Brate et al. 2016, Walkinshaw et al. 2020). When plastic particles are mistaken for prey, effective feeding is reduced, and can in turn lead to lowered energy levels (Anbumanu and Kakkar 2018, Carlos de sá et al. 2018). Once ingested, microplastic particles may be retained in the digestive tract or pass through the gastrointestinal tract and land in the stomach (Caruso et al. 2018, Lusher et al. 2016) and sometimes liver (Anbumani and Kakkar 2018).

Microplastics have the potential to block the gastrointestinal track of Atlantic cod, which induce an inflammatory response, oxidative stress, or a false sense of satiation (Anbumani and Kakkar 2018, Au 2017, Brate et al. 2016). Microplastic particles can remain in the fish for up to four days, so toxins and chemicals in plastics may affect the fish for the duration of this time (Brate et al. 2016, Lusher et al. 2016, Rummel et al. 2016). These toxins can lead to endocrine disruptions (Anderson et al. 2016), alter intestinal tissues (Anbumani and Kakkar 2018), cause abnormal swimming patterns and lethargy (Anderson et al. 2016), and alter immune functions (Caruso et al. 2018). Mattsson et al. (2015) studied the impacts of feeding Crucian carp (*Carassius carassius*) nanoplastics and found that the fish had heavier swollen brains with increased water levels. It is likely that similar effects would be observed if Atlantic cod due to the tendency of microplastics to accumulate in lipid rich organs (Anderson et al. 2016). These changes caused by microplastics can combine to negatively affect reproductive success of the species and increase stress (Bessa et al. 2018, Carlos de sá et al. 2018).

Blue Mussel

Species that exhibit filter feeding, such as the blue mussel, are highly susceptible to passively take in microplastics with their normal food (Rist et al. 2018, Rist et al. 2019), specifically floating, low density particles (Choy et al. 2019, Van Cauwenberghe et al 2015). Choy et al. found that microplastics are generally in greatest concentration between depths of 200 and 400 meters, which overlaps with the habitat of adult blue mussels. Although the blue mussel is a selective feeder, meaning it chooses to ingest only appropriate particles and eliminate those that are unwanted, this selection process is not perfect (Rist et al. 2018, Van Cauwenberghe et al. 2015, Woods et al. 2018). Two main methods of microplastic uptake are exhibited by the species. The more likely of the two is direct transport of particles into the gills during feeding, while the other possibility is a secondary pathway to the stomach caused by ciliate movement (Browne et al. 2008, von Moos et al. 2012). The occurrence of ingestion is impacted by multiple factors including the size, shape, and concentration of the plastic particle (Rist et al. 2018, Rist et al. 2019, Van Cauwenberghe et al. 2015). Multiple studies have noted instances of ingestion, accumulation, and translocation specifically of polystyrene particles within blue mussels (Anbumani and Kakkar 2018, Browne et al. 2008, Hantoro et al. 2019, Rist et al. 2019, Van Cawenberghe et al. 2015), indicating this may be one of the particle types the species is more susceptible to ingesting.

Once ingested, microplastics have been found to induce adverse effects on bivalves such as the blue mussel (Bour et al. 2018, Green et al. 2019, Rist et al. 2018, Rist et al. 2019, Woods et al. 2018, Van Cauwenberghe et al. 2015). Ingested microplastics can translocate, which is the transfer of a particle across a barrier, from the gut to the circulatory system and tissues. Microplastics tend to accumulate within areas of the blue mussel such as the gut, digestive cavity, circulatory system, and tubules (Anbuman and Kakkar 2018, Browne et al. 2008, Van Cauwenberghe et al. 2015). Due to their size, smaller particles have a greater likelihood of translocating throughout the body, possibly making them more dangerous than their larger counterparts (Rist et al. 2019, Van Cauwenberghe et al 2015). After translocation from the gut to the circulatory system, a process that takes as little as three days, microplastics can persist for upwards of 48 days in the mussels' system (Anbumani and Kakkar 2018, Browne et al. 2008, Rist et al. 2019). As microplastics interact with the individual for this extended period they have the potential to cause adverse effects, especially those particles containing high concentrations of toxins or chemicals (Browne et al. 2008, Guzzetti et al. 2018, Van Cauwenberghe et al. 2015).

Although no significant alteration to protein, lipid, or carbohydrate levels have been observed in exposed blue mussels (Bour et al. 2018, Van Cauwenberghe et al 2015), a variety of other changes have been noted including a large decrease of the stability of the lysosomal membrane (Anbumani and Kakkar 2018, von Moos et al. 2012), inflammatory responses (Anbumani and Kakkar 2018, Bour et al. 2018, Rist et al. 2019, Van Cauwenberghe et al. 2015), oxidative stress (Rist et al. 2019), and reduced feeding and filtering activity (Bour et al. 2018, Rist et al. 2019, Van Cauwenberghe et al. 2015). Green et al. (2019) also noted the reduced production and function of byssal threads of blue mussels exposed to microplastics, and a reduction of their attachment ability and habitat availability. A study focusing on blue mussel larvae found that microplastic exposure had no impact on growth rates of larvae, yet higher rates of abnormal development were noted (Rist et al. 2019). In the case of blue mussels being exposed to very high concentration of microplastics, the mussels will completely stop filtering activity by closing their valves. But these conditions only exist in laboratory settings (Woods et al. 2018). Overall, these effects could lead to significant stress, starvation, and potentially the death of blue mussels (Browne et al. 2008, Van Cauwenberghe et al. 2015, Woods et al. 2018).

METHODS

The Atlantic cod and blue mussel were selected for their ability to represent two vastly different lifestyles and feeding strategies within the marine habitat. In order to understand the effects that microplastics have on Atlantic cod and blue mussels, it was first important to obtain a base knowledge of their lifestyles and function, as well as the possible microplastic polymers, shapes, sizes and their presence and interactions with the environment. This baseline understanding was obtained through the use of books, academic articles, and online sources. The majority of these sources were accessed through the Lakehead University library website which provides access a variety of databases including the Academic Search Premier, eBook Collection, Education Resource Information Center (ERIC), GreenFILE, Education Source, and OpenDissertations. After searching these databases for relevant sources, further specifications were made regarding year of publication or selecting for peer reviewed sources, which are deemed more reliable. The screening of abstracts was done to determine relevant sources that could potentially be used. Those relevant sources were selected and within them the literature cited sections were used to obtain more potentially relevant sources. Google scholar was also used to identify further relevant academic sources.

Independent searches to collect all further necessary information, including feeding strategy, preferred habitat, and possible interactions of each species interaction with microplastics was completed prior to beginning the comparison between Atlantic cod and blue mussels. The potential effects on the two species was studied through the literature review process, which was separated into the main categories of methods of uptake and toxicity. These presented the basis of understanding for the potential impacts that each species could face.

Photos were collected from online and peer reviewed academic sources or articles. The information needed to complete tables was collected and/or complied from one or multiple academic sources. Any desired tables and charts were then produced in excel.

RESULTS

Microplastics Within the Water Column

Blue mussels were found to have a greater chance of ingesting microplastic particles than Atlantic cod, as the concentration of microplastics is generally higher in the preferred habitat of mussels. Figure 5 presents the concentration of particles at varying depts of the water column. The number of particles are highest between depths of 200 and 600 meters, and much lower at areas above the ocean floor and the surface. Although the exact number of particles will vary with each location sampled, it shows a general trend of the variation in microplastic concentration throughout the water column.

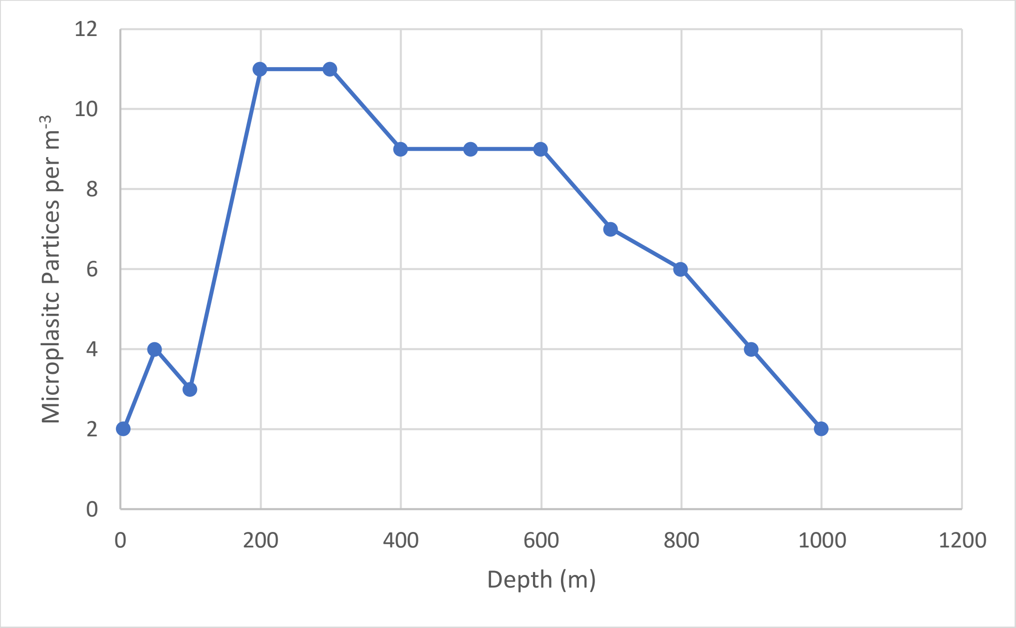

Figure 5. Microplastic concentrations throughout the water column with depth of 1600m (Source: Choy et al. 2019).

Interaction of Microplastics With Species

The length of time that ingested particles remain in the system of blue mussels is much greater than the time they remain in the system of Atlantic cod. From the time of intake to the time of egestion, a microplastic can take upwards of 48 days to pass through a blue mussel, while the process only takes up to four days in an Atlantic cod (Table 4). The retention time of microplastics within each species as well as the organs they pass through are noted in Table 4 (Anbumani and Kakkar 2018, Brate et al. 2016).

Table 4. Interaction of microplastic particles with internal systems of both species (Source: Anbumani and Kakkar 2018, Anderson et al. 2016, Au 2017, Brate et al. 2016, Browne et al. 2008, Caruso et al. 2018, Green et al. 2019, Lusher et al. 2016, Rist et al. 2019, Rummel et al. 2016, Van Cauwenberghe et al. 2015, Woods et al. 2008).

Species	Organs Impacted	Time in System
Blue Mussel	gut, circulatory system	>48 days
Atlantic Cod	digestive tract, stomach, liver (sometimes)	up to 4 days

Atlantic cod have only been recorded to ingest fragments and fibres, while blue mussels have been noted to ingest spheres, flakes, filaments, and foils, as well as fragments and fibres. Also, microplastic particles ingested by Atlantic cod are made of a less diverse range of polymers than those ingested by blue musses (Table 6). The full name of each ingested polymer type is presented in Table 5. Individual blue mussels have also reached much higher concentrations of microplastics than Atlantic cod (Table 6).

Blue mussels seem to intake a wider variety of shapes and forms of microplastics made from a broader array of polymer types. Blue mussels have been noted to ingest three times the number of shapes and polymer types of microplastic particles than Atlantic cod (Figure 6).

The Atlantic cod sampled in the North Sea and Baltic Sea of Denmark contained the highest number of microplastic shapes and polymer types. Both fragments and fibres of polyurethane, polystyrene, polypropylene, and polyethylene (Lenz et al. 2016). Comparatively, only fragments of an unrecorded polymer were found in the cod sampled from the eastern coast of Newfoundland (Liboiron et al. 2016).

Blue mussels sampled from China's coastline contained the greatest number of microplastic shapes, with fibres, fragments, spheres, and flakes all ingested (Li et al. 2016). Those sampled in Belgium (fibres) (De Witte et al. 2014), the North Sea of Germany (spheres) (Van Cauwenberghe and Janssen 2014), France, Belgium, and the Netherlands (spheres) only contained one particle shape (Van Cauwenberghe et al. 2015). The greatest number of polymer types (acrylonitrile butadiene styrene, polyester, polymethylmethacrulate, polystyrene, copolymer, polyethylene, polypropylene) were found in the blue mussels sampled off the Atlantic coast of France (Phoung et al. 2017). The lowest variety of polymer types were found in the mussels sampled from China's coastline (cellophane, polyethylene terephthalate, polyester) (Li et al. 2016), and those sampled from the North Sea of France, Belgium, and the Netherlands (low-density polyethylene, high-density polyethylene, polystyrene) (Van Cauwenberghe et al. 2015). The highest concentration of microplastic particles (34) was found in the individuals sampled in the Halifax Harbour of Nova Scotia (Mathalon and Hill 2014). Comparatively only 1.5 particles were found in blue mussels sampled from China’s coastline (Li et al. 2016)

Table 5. List of polymer types.

Acronym	Polymer Type
ABS	Acrylonitrile butadiene styrene
CP	Cellophane
HDPE	High-density polyethylene
LDPE	Low-density polyethylene
PA	Polyamide
PE	Polyethylene
PET	Polyethylene terephthalate
PL	Polyester
PMMA	Polymethylmethacrulate
PP	Polypropylene
PS	Polystyrene
PU	Polyurethane

Table 6. Types and concentration of microplastics found within species (Source: De Witte et al. 2014, Hantoro et al. 2019, Lenz et al. Li et al. 2016, Liboiron et al. 2016, Mathalon and Hill 2014, Phuong et al. 2017, Van Cauwenberghe and Janssen 2014, Van Cauwenberghe et al. 2015).

Species	Concentration (#/animal)	Shape / Form	Polymer Type
Atlantic Cod	1-2	fragment, fibre	PU, PS, PP, PE
Blue Mussels	1.5-34	fibres, fragments, spheres, flakes, filaments, foils	CP, PET, PL, PP, PE, LDPE, HDPE, PS, PMMA, ABS, PA, copolymer

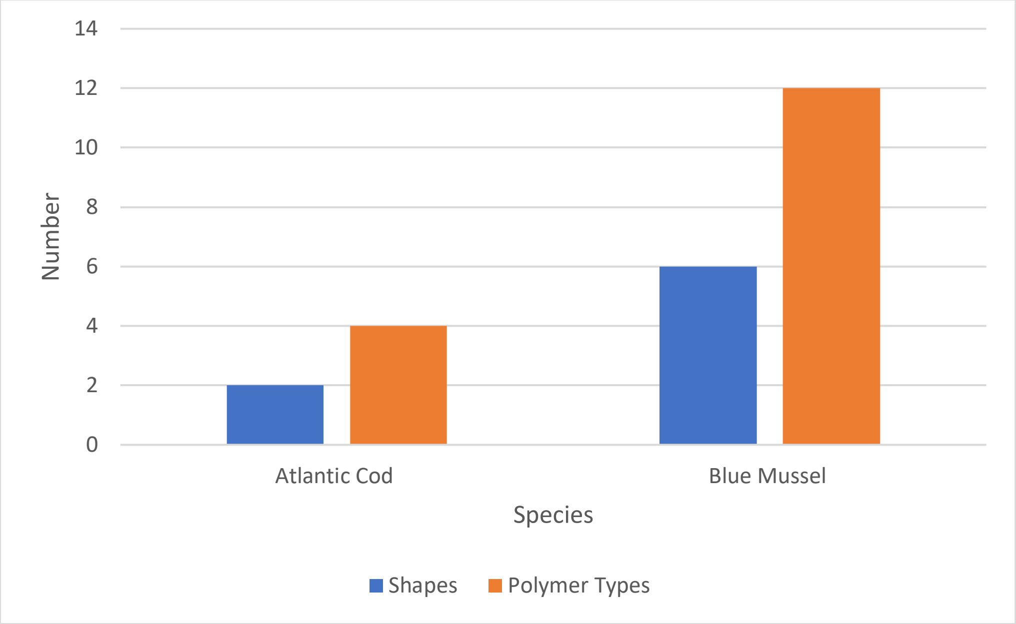

Figure 6. Comparison of the recorded number of shapes and polymer types that have been ingested by each species (Source: Hantoro et al. 2019).

A number of effects have been noted to occur in both Atlantic cod and blue mussels as a result of microplastic ingestion. They also share a number of like effects, some more serious than others, with the increased probability of mortality being the most serious result of all for both species (Table 7). The probability of mortality is increased for both species due to the alteration to their systems and overall function resulting from the ingestion of microplastics (Carlos de sá et al. 2018).

The number of effects that have been found to occur as a result of microplastic ingestion, based upon the observed results from 26 studies, are the same for both blue mussels and Atlantic cod. Twelve impacts are characteristic of both species (Figure 7). These twelve effects are altered feeding behaviour, altered function of the immune system, behavioural changes, contamination due to chemicals or additives, increased probability of mortality, increased stress, specifically oxidative stress, increased predation risk, inflammation, possible starvation, reduced energy acquisition, and reduced reproductive success (Table 7).

Table 7. Noted effects to occur in species as a result of microplastic ingestion. Those found to occur are identified by ‘x’ (Source: Almroth and Eggert 2019, Anbumani and Kakkar 2018, Anderson et al. 2016, Au 2017, Bessa et al. 2018, Bour et al. 2018, Brate et al. 2016, Browne et al. 2008, Carlos de sá et al. 2018, Caruso et al. 2018, EFSA 2016, Green et al. 2019, Hantoro et al. 2019, Kerscher 2019, Lusher 2015, Lusher et al. 2017, Melvin 2017, Peng et al. 2020, Rist et al. 2018, Rist et al. 2019, Rummel et al. 2016, Van Cauwenberghe and Janssen 2014, Van Cauwenberghe et al. 2015, von Moos et al. 2012, Walkinshaw et al. 2020, Woods et al. 2018).

	Species	
Effects of Microplastic Ingestion	Atlantic Cod	Blue Mussel
Abnormal swimming	x	
Accumulation in gut		x
Alter feeding behaviour	x	x
Alter function of immune system	x	x
Behavioural changes	x	x
Block gastrointestinal tract	x	
Contamination by chemicals/additives	x	x
Decreased filtering activity		x
Decreased production and function of byssal threads		x
Disrupt digestive system		x
Disrupt endocrine system	x	
Increase of abnormal development in larvae		x
Increased respiration		x
Increased predation risk	x	x
Increased probability of mortality	x	x
Increased production of pseudofaeces		x
Increased stress	x	x
Lethargy	x	
Inflammation	x	x
Liver stress	x	
Lysosomal membrane destabilization		x
Oxidative Stress	x	x
Possible Starvation	x	x

Table 7. Noted effects to occur in species as a result of microplastic ingestion. Those found to occur are identified by 'x'.

	Species	
Effects of Microplastic Ingestion	Atlantic Cod	Blue Mussel
Reduced predatory performance	x	
Reduced reproductive success	x	x
Slower growth	x	
Visual and morphological changes to brain	x	

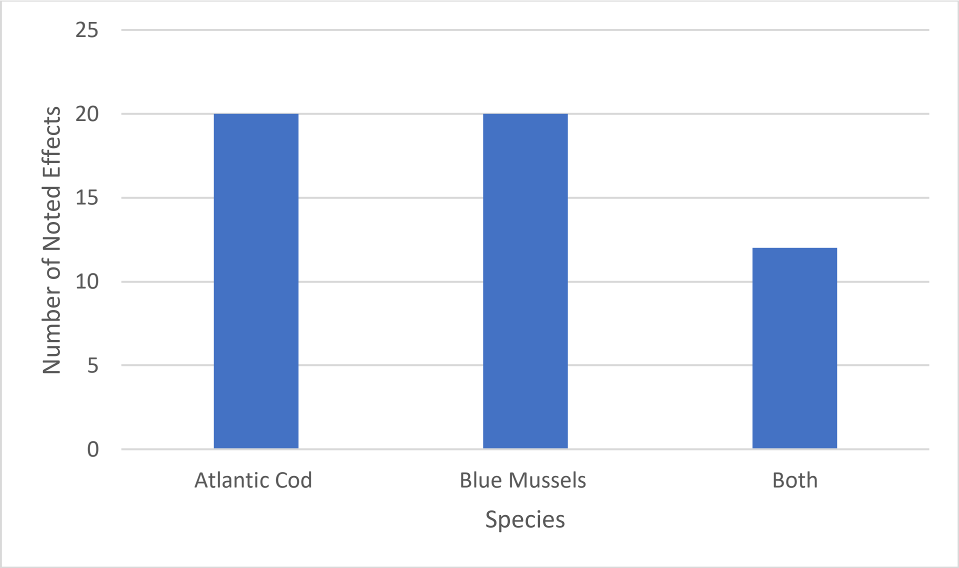

Figure 7. Number of negative effects noted to occur in both species and the effects shared by both blue mussels and Atlantic cod (Source: Anbumani and Kakkar 2018, Anderson et al. 2016, Au 2017, Bessa et al. 2018, Bour et al. 2018, Brate et al. 2016, Browne et al. 2008, Carlos de sá et al. 2018, Caruso et al. 2018, Green et al. 2019, Rist et al. 2019, Rummel et al. 2016, Van Cauwenberghe et al. 2015, von Moos et al. 2012, Woods et al. 2018).

DISCUSSION

Species Contact with Microplastics

Likelihood of Contact

Due to their feeding strategy and habitat preferences, Atlantic cod are less likely to ingest microplastics when compared to blue mussels. Both species inhabit nearshore areas and generally face greater amounts of plastic pollution due to human activity (Almroth and Eggert 2019). However, as a benthopelagic species, Atlantic cod are likely to avoid both low- and high-density particles found near the upper and lower levels of the water column respectively (Liboiron 2016).

Alternatively, blue mussels tend to inhabit areas ranging from shallow estuaries to deeper offshore waters in depths up to 500 m (Fisheries and Oceans Canada 2003). The portion of the water column between 200 and 600 m in depth has been found to contain the highest levels of microplastics (Figure 5). This location directly overlaps with the preferred habitat of blue mussels. Even in the shallower estuary depths that mussels often inhabit there is still relatively high concentrations of microplastics (Figure 5). Although Atlantic cod are generally found at depths less than 400 m, as that is the depth of the benthopelagic zone in nearshore waters off the east coast of Canada (COSEWIC 2010), that does not necessarily mean their habitat also overlaps with the area of greatest microplastic concentration. The depth of the ocean floor of the water column for the data presented in Figure 5 was 1600 m. In this case the benthopelagic zone would reach the area around the last point of data available, at a depth of 1000 m. The levels of microplastics at this depth are much lower than those of the rest of the water column. Liboiron (2016) noted that as a benthopelagic species, Atlantic cod may have a reduced likelihood of encountering high-density plastic particles that settle at the ocean floor and low-density particles at the top of the water column. The findings presented in Figure 5 are consistent with the point made by Liboiron (2016), in that the lifestyle of Atlantic cod allows them to avoid a large number of microplastic particles.

The lower concentration of particles that Atlantic cod likely encounter could provide reasoning for the difference of up to 33 particles that have been found in the two species. One to two microplastic particles have been found in tested Atlantic cod, while up to 34 particles have been found in blue mussels (Table 6). If there is a lower concentration of microplastic particles in a species preferred habitat, they will be less likely to ingest particles and in turn ingest fewer particles over their lifetime. The reduced probability of contact that Atlantic cod seem to have with microplastics could lead to less significant effects to the species as a result of microplastic particles.

Forms of Microplastic Particles

Compared to Atlantic cod, blue mussels have been found to ingest a wider variety of both shapes and types of microplastics (Figure 6). Records of microplastic ingestion have found that Atlantic cod consume only fragments and fibres made of polyurethane, polystyrene, polypropylene, or polyethylene polymers (Table 6). Microplastic particles in the ocean are found in a variety of forms, so consuming only two forms eliminates the capability of a number of plastics from harming the species.

However, the majority of plastics found in the ocean are made of either polypropylene, polyethylene, polyvinylchloride, polyurethane, polyterephthalate, or polystyrene (Almroth and Eggert 2019). Each one of the four polymer types known to be consumed by Atlantic cod are on this list, so consequently they are able to consume those polymers that are in highest concentration.

Comparatively, blue mussels ingest triple the number of microplastic shapes than Atlantic cod, with fragments, fibres, spheres, flakes, filaments, and foils all on the list. Blue mussels also ingest microplastic particles made of cellophane, polyethylene terephthalate, polyester, polypropylene, polyethylene, low-density polyethylene, high-density polyethylene, polystyrene, polymethylmethacrylate, acrylonitrile butadiene styrene, polyamide, and copolymer polymers (Table 6). However, of the list of possible ingested polymer types only four are on the list of the six most common types of plastic particles in the ocean (Almroth and Eggert 2019). This is equal to that of Atlantic cod. Both species are exposed to the majority of particle types found in highest concentration in the ocean, which is disadvantageous for both. However, blue mussels may still be exposed to more microplastics as they consume a greater number of particle shapes than Atlantic cod (Figure 6).

Ingestion of Microplastics

Blue mussels can intake microplastic particles through either direct ingestion, which is most common, or through a secondary pathway (von Moos et al. 2012). During the imperfect selective filter feeding process exhibited by mussels, unwanted particles are still taken up (Rist et al. 2018). Van Cauwenberghe et al. (2015) found that in one day blue mussels filter almost 24 liters of water, and could be exposed to an estimated ten microplastic particles. Although this number is variable depending on exact habitat conditions, this daily intake of plastic particles can lead to a build-up of microplastics in their system. It also amounts to a significant number of particles that impact a blue mussel throughout its lifetime. When a particle is ingested it is transported to the gut and in as little as three days it can travel to the circulatory system (Browne et al. 2008). Movement is size dependent as smaller particles are more likely to translocate to other parts of the body due to their increased likelihood of crossing biological barriers (Rist et al. 2019). The particle can then persist in the circulatory system for upwards of 48 days until it is egested (Table 4).

As is the case with blue mussels, Atlantic cod can ingest microplastic particles directly or through secondary ingestion. This generally occurs when the fish confuse plastic particles for prey or by consuming contaminated prey (Lusher et al. 2017). Due to their larger size and feeding strategy, Atlantic cod are able to ingest microplastics of larger sizes than blue mussels (Rist et al. 2018). The likelihood and occurrence of microplastic ingestion depends on prey choice and the exact habitat of each individual, as the vulnerability of a fish to confuse microplastics for prey is likely to be impacted by habitat features (Anderson et al. 2016). Once ingested, a microplastic particle can either remain in the digestive tract or travel through the intestine to the stomach, or in less frequent cases the liver (Table 4) (Anbumani and Kakkar 2018). It can remain in the system of Atlantic cod for up to four days (Table 4) before it is removed through the stomach evacuation process or with the remainder of other undigested materials (Lusher et al. 2016).

Microplastics remain within the system of Atlantic cod for a significantly shorter period of time than they persist in blue mussels (Table 4). Because of this microplastics may have less time to impact Atlantic cod. This could lead to more adverse impacts to blue mussels, especially when particles contaminated with chemical additives and environmental contaminants are ingested. Any toxins will have a prolonged effect throughout the span of the 48 days that microplastics are present in the system of blue mussels (Table 4), and could potentially transfer to many tissues through the open circulatory system in that time (Browne et al. 2008). While contaminated particles ingested by Atlantic cod also leach out toxins for the duration of time they are in the fish, this period of time is 44 days shorter than that of the blue mussel (Table 4). This more rapid egestion rate is likely to be beneficial for Atlantic cod.

Potential Effects of Microplastic Ingestion

The severity of each potential effect of microplastic ingestion described below is dependent upon the concentration of microplastics that the individual is exposed to. Most of the potential effects are associated with other impacts due to the connectivity of species systems. Each of these responses, either individually or working in conjunction with others, alters the system of the individual and therefore increases its probability of mortality (Table 7) (Anbumani and Kakkar 2018).

Feeding Behaviour

The ingestion of microplastic particles can potentially alter the feeding behaviour in both Atlantic cod and blue mussels (Table 7). In the case of Atlantic cod, this occurs when microplastic particles are mistaken for prey. The ingestion of microplastics as pseudo-prey leads the fish to a mistaken sense of satiation (Brate et al. 2016), and as a result their food consumption levels are reduced (Anbumani and Kakkar 2018). Notably, an individual will not acquire sufficient energy (Table 7), and as a result lethargic behaviour will be exhibited (Anderson et al. 2016). Furthermore, lethargy, a state of reduced energy or inactivity, can lead to reduced predatory performance, as the predator will not be able to chase and catch prey (Carlos de sá et al. 2018).

As adult Atlantic cod are one of the top predators in the benthopelagic zone of the ocean, successful predatory performance is a highly important and necessary behaviour for the species (Oceana 2019). As Atlantic cod rely on prey to sustain their diet, if predatory performance significantly decreases then an individual faces the possibility of starvation (Table 7) (Anbumani and Kakkar 2018). Starvation is an extreme possible side effect that Atlantic cod could face due to microplastic ingestion, however the chance of this occurring is low and would most likely require a high intake of particles to reach this point.

Blue mussels, like other filter feeders, are highly susceptible to intaking microplastics with their normal food while filter feeding (Rist et al. 2019). When exposed to microplastics, blue mussels reduce their filter feeding activity (Table 7). If the microplastic concentration becomes too high, they will stop filtering altogether by closing their vales. Although these conditions have so far only occurred in a lab setting, with ocean plastic levels increasing daily this could very well be the case in the world's oceans of the future (Woods et al. 2018).

Exposure to microplastics also significantly increases the number of pseudofaeces produced (Table 7), which are particles that are wrapped in mucus and egested prior to passing through the digestive tract as they cannot be consumed as food (Van Cauwenberghe et al 2015). This decreased filtering activity coupled with the increased production of pseudofaeces of particles that are filtered leads to a loss of food intake. Like Atlantic cod, with reduced food intake comes inadequate levels of energy. Blue mussels could experience starvation with exceedingly high concentrations of microplastics (Table 7).

The reduction of filtering activity seen in blue mussels is comparable to the decreased predatory performance exhibited by Atlantic cod as both result in the decreased consumption of food. The severity of negative effects faced by each species is dependent on the amount of microplastic particles they are in contact with (Lusher et al 2017). As blue mussels are seemingly exposed to a greater concentration of microplastics (Figure 5) and their feeding strategy makes them highly susceptible to microplastic intake (Rist et al. 2019). From the above evidence, it seems that blue mussels may endure a more severe level of impacts than Atlantic cod.

Byssal Thread Function

Byssal threads are secreted by the foot of blue mussels allowing it to anchor to either a stable substrate or another mussel (Newell 1989). This is a highly important feature of a successful blue mussel population, and mussels exposed to microplastics decreased both the number of byssal threads generated and the tenacity of the individual by 50 percent. This is significant, as the production of properly functioning byssal threads allows blue mussels to form aggregations (Green et al. 2019). The species spawns through the release of male gametes followed by egg release into the water column where fertilization occurs (Fisheries and Oceans Canada 2003). As such, aggregations increase fertilization success due to the close proximity of a large number of individuals. The large number of individuals found in aggregations also provides protection against predators (Green et al. 2019). This is highly beneficial as the most important mortality cause among blue mussels, especially those which are younger and smaller, is predation (Walters 2008). If an individual is not able to aggregate it is highly exposed to predators and its fertilization success is reduced. Also, the populations that depend on reefs for space will suffer a loss of habitat availability. As a result, the exposure of blue mussels to microplastics leads to the reduced production and function of byssal threads and could increase their likelihood of mortality (Green et al. 2019).

The Brain

An effect to the brain due to microplastic exposure is one that only impacts Atlantic cod, as blue mussels do not have a brain (Table 7). Although no studies have directly focused on the repercussions microplastic ingestion has on the brains of Atlantic cod, other marine fish have exhibited changes to the brain. Those who were fed microplastic particles showed visual and morphological changes (Mattsson et al. 2015). The brains had an increased water content and weight, swelled, and changed in colour after continued ingestion of plastic particles. This is because microplastics have the ability to disturb biological membranes and are often trapped in organs, such as the brain, that are rich in lipids (Anderson et al. 2016).

As the brain is debatably the most important organ, a change in brain morphology often induces further effects that can have significant consequences. Fish who showed changes to the brain also exhibited behavioural changes, namely in activity and predatory function (Mattsson et al. 2015). As previously noted, predatory ability is highly important for Atlantic cod, so a decline in this ability can have serious consequences, including lack of energy and starvation at the extreme (Anbumani and Kakkar 2018). Although this side effect has yet to be studied specifically in Atlantic cod, it is likely that continued microplastic ingestion will lead to changes in the brain and further impacts like those exhibited in other species of similar marine fish. It is unknown whether a high enough concentration of microplastics exists in the natural environment to lead fish to consume the amount of particles required to induce significant impacts to their brain (Anderson et al. 2016).

Contamination by Chemical Additives and Natural Contaminants

Blue mussels and Atlantic cod consume microplastics containing both chemical additives and natural contaminants, and thus the two species are susceptible to contamination from the toxins found in particles (Table 7). Plastics are capable of containing concentrations of chemicals up to ten times as high as natural substances, which increases their chance of acting as a route of contamination to organisms (Van Cauwenberghe et al. 2015). Polyaromatic hydrocarbons (PAH), polychlorinated biphenyl (PCB) and dichlorodiphenyltrichloroethane (DDT) are examples of toxic chemicals located in the world's oceans that plastics readily absorb (Browne et al. 2008). Heightened exposure to these chemicals can lead to a variety of effects depending on the type of chemical, its concentration, and interaction with the species. Generally, chemical exposure affects neurological, behavioural, and reproductive functions (Lenntech 2020). Overall, chemical exposure via plastics occurs in relatively low doses. As the concentration of toxins are not high enough to cause immediate death to the species, exposure over long periods of time often leads to chronic effects (Lenntech 2020).

In the case of blue mussels, chemical additives and natural contaminants found in microplastics can impact an individual for upwards of 48 days (Table 4). During this time it is possible for the toxins to transfer to a number of tissues and organs (Browne et al. 2008). One study estimated that per gram of tissue, blue mussels can intake an additional 0.0006 nanograms of PCBs solely from plastics (Van Cauwenberghe et al. 2015). This supplementary exposure to toxins can invoke dangerous consequences, especially as they can persist in the individual for an extended period of time (Browne et al. 2008). The lysosomal membrane and lysosomes, which are involved in the waste removal and digestion process, are capable of accumulating high levels of contaminants, but the lysosomal system is highly sensitive to minimal amounts of pollutants (Martinez-Gomez et al. 2015). As a result, exposure to microplastics and their contaminants results in the destabilization of the lysosomal membrane (Table 7), which occurs at both the cellular and subcellular levels (von Moos et al. 2012). The destabilization generally happens after 96 hours of exposure to microplastic particles, which is well within the time period that the particles are retained within blue mussels (Anbumani and Kakkar 2018). Consequently, lysosomal membrane destabilization will reduce the functionality of the immune system, alter the digestive system, affect the feeding behaviour of the organism, and leads to swelling of the lysosomes. These resulting changes will affect the overall function and well-being of the organism (Martinez-Gomez et al. 2015).

Similarly, Atlantic cod can be exposed to the toxins found in microplastics for the duration of their gut retention period, which is four days (Table 4). Although studies have not directly focused on Atlantic cod, they have noted the impacts of toxins in plastics to other similar marine fish, so it is expected that cod will endure similar effects. When in the digestive system of the fish, microplastics and the toxins they carry are in immediate contact with its digestive fluids. This increases the possibility for the toxic substances to transfer throughout the body (Brate et al. 2016). Also, certain chemicals including phthalates and bisphenol A (BPA) act as endocrine disrupters in fish (Table 7) (Anderson et al. 2016). The endocrine system regulates metabolism, growth, reproductive function, and activity. As a result, disruption of this system will affect each of these functions (Almroth and Eggert 2019). Chemicals can also impact the function of the immune system, which in turn affects the overall well-being of the individual (Caruso et al. 2018). As toxins bioaccumulate, another factor to consider is the position of Atlantic cod in the food chain. As adults they are one of the top predators in the benthopelagic zone (Oceana 2019), so they can potentially take up greater concentrations of chemicals if they consume contaminated prey (Anbumani and Kakkar 2018).

Both cod and mussels are likely to suffer some similar effects including reduced immune system function and alteration of organs or systems functions which can impact their general health. It is difficult to conclude which of the two species will face more severe consequences arising from contamination by toxins. Atlantic cod can potentially face severe effects due to bioaccumulation and because chemicals found in microplastics disrupt the endocrine system of fish resulting in a multitude of repercussions (Anderson et al. 2016). However ingested particles, and therefore any contaminants they contain, persist in blue mussels much longer than they do in Atlantic cod (Table 4). This prolonged exposure could increase the severity of effects, especially once the lysosomal membrane is affected (von Moos et al. 2012).

Growth and Development

The growth and development of both species can be affected when exposed to microplastics for a variety of reasons including increased stress, abnormal feeding behaviour, altered function of organs and systems, and reduced energy acquisition. In the case of blue mussels, their growth rate is not affected, but the development of larvae is (Table 7). Although abnormal larval development occurs even when not exposed to microplastics, the portion of those showing abnormalities increases with exposure. When exposed to microplastics, abnormal development was exhibited in 40 percent to 60 percent of larvae. Furthermore, abnormal developments may also lead to additional effects including alteration of larval dispersion, dwelling, and subsequent developments (Rist et al. 2019).

In contrast, exposure to microplastics can slow growth rates in Atlantic cod (Table 7). This could impact their success as a predator and heighten their vulnerability to predators. A reduction in growth rate will increase the amount of time it takes to become a top predator, which may further hinder the ability of the individual to obtain adequate food sources. It will also increase their susceptibility to other predators (Table 7); as juveniles, Atlantic cod are preyed upon by a variety of species and when growth rates are slowed. Also, the cod will be available to these predators for an extended period of time (Oceana 2019).

Stress

As microplastics are a foreign substance to both species, ingestion can induce stress (Table 7). Stress can occur as a secondary factor due to altered system function that results when microplastics are ingested (Van Cauwenberghe et al. 2015). Stress can also be a factor leading to many of the negative impacts previously listed, including decreased immune system function, altered feeding, and reduced reproductive success. After exposure to microplastics, oxidative stress has been exhibited in both blue mussels and Atlantic cod (Anbumani and Kakkar, Rist et al. 2019). Oxidative stress occurs when there is an imbalance of free radicals and antioxidants, which can lead to further complications including inflammation, disease, or alterations in the function of the circulatory system (Betteridge 2000).

Blue mussels intake microplastics they need to expel more energy to maintain homeostasis, and in turn respiration is increased. (Table 7) (Van Cauwenberghe et al. 2015). This is contradictory to the observed response of mussels to reduce or even stop filtering activity. Therefore, reducing energy intake, which occurs when exposed to a high concentration of microplastics (Woods et al. 2018) may cause increased energy consumption. This in turn may directly compensate for increased stress in the individual taking place under lower concentrations of microplastics compared to the other study (Van Cauwenberghe et al. 2015). This demonstrates the range of possible effects that can occur when species are exposed to microplastics, and the uncertainty of what will occur.

When microplastics are ingested and accumulate within Atlantic cod, their internal system becomes stressed. Although not incredibly frequent, particles may translocate to the liver and place the organ under stress (Anbumani and Kakkar 2018). For example, studies based on other similar marine fish, but not Atlantic cod specifically, noted that when particles reached the liver, the organ became stressed (Table 7) (Anderson et al. 2016). This stress led to changes in the liver such as depletion of glycogen, the formation of fatty vacuoles, and single cell necrosis (Anderson et al. 2016).

After ingesting microplastics, both Atlantic cod and blue mussels exhibited levels of increased stress, specifically oxidative stress (Table 7). Increased stress in both species can potentially lead to further complications. Atlantic cod exhibited higher stress in the liver; blue mussels showed increased respiration to combat stress levels affecting their ability to maintain homeostasis (Anderson et al. 2016, Van Cauwenberghe et al. 2015).

Inflammation

Inflammatory responses are exhibited by both Atlantic cod and blue mussels when microplastics are ingested (Table 7). Inflammation is swelling that occurs during the process of healing damaged tissues. Small amounts of inflammation are not generally problematic, however lasting inflammation can be damaging to organs (Chen et al. 2018). Within six hours of ingesting a microplastic particle, blue mussels exhibit inflammation (Anbumani and Kakkar 2018). A collection of cells, known as a granulocytoma, is formed by the tissues to combat damages from the microplastic (von Moos et al. 2012). Similarly, inflammatory responses are exhibited in Atlantic cod when microplastics accumulate and thin the epithelium of the intestine. The accumulation of plastic particles thins the tissue lining which provokes inflammation (Anbumani and Kakkar 2018). Inflammation can occur anywhere within the body of either species were microplastics can translocate to and induce tissue damage. This could result in more severe inflammatory responses exhibited by blue mussels, especially when smaller particles are ingested, as their open circulatory system allows for a greater translocation of particles (Rist et al. 2019).

CONCLUSIONS

The presence of microplastics in the marine environment adversely affects Atlantic cod and blue mussels in a variety of ways. As distinct variations were found to occur between the effects exhibited in Atlantic cod and blue mussels, the null hypothesis is rejected. The effects that occur, and their severity, depends upon the exact habitat of the individual and the concentration of microplastics that occurs (Anbumani and Kakkar 2018). For example, under different conditions blue mussels were observed to decrease or stop filtering activity, which in turn reduced energy intake, and have also been observed to increase energy consumption to compensate for stress caused to internal systems (Van Cauwenberghe et al. 2015).

The conditions of the world's oceans with respect to the presence of microplastics is relatively unknown. To date, studies regarding the levels of microplastics throughout the water column are fairly limited as this is a relatively new area of research. Furthermore, most studies that have been done focused their efforts on microplastic concentrations only at the surface of the ocean. Also, current technologies are incapable of detecting particles smaller than 0.01 mm in size, so the concentration of the smallest microplastics continues to be unknown (Rist et al. 2019). For these reasons, it is difficult to determine the exact severity of effects organisms will endure.

Atlantic cod and blue mussels each exhibit twenty major effects when exposed to microplastics, however twelve of these are overlapping with the impact being highly similar to that of the other species (Figure 7). Even though over half of the total effects to each species were overlapping, the reaction the two species had to the presence of microplastics was different. Overall, the two species exhibit varied effects to their systems after the ingestion of microplastics. However, this is expected as Atlantic cod and blue mussels possess different lifeforms and behaviours. Many side effects of microplastic ingestion result from other induced changes, so it is usually not just one definitive change that occurs to the individual, rather a variety of effects influencing one another (Anbumani and Kakkar 2018). Also, secondary effects often vary between the two species as their internal systems respond differently to the disturbance caused by microplastic ingestion. Each of the resulting impacts has negative connotations to the livelihood of the individual, and if they become severe enough can lead to or increase the probability of mortality (Lusher 2015).

This information is beneficial to other marine species, especially other species of molluscs and benthopelagic fish, as it provides insight into the effects that might occur in other closely related species. Also, because blue mussels are an ecosystem indicator the severity of effects they exhibit can be a good measure of the conditions of an area and what is to come for other species.

Further research needs to be completed regarding the amount of microplastics throughout the water column in order to predict the effects that marine species will endure. There is also a large gap between the research that exists on the two species. Blue mussels are one of the most studied bivalves with respect to interaction with microplastics because it is deemed an ecosystem indicator (Van Cauwenberghe et al.

2015). Due to this, there is much more research regarding the specific possible effects to blue mussels as compared to Atlantic cod.

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