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Microplastic Occurrence and Effects In Commercially Harvested North American Finfish and Shellfish: Current Knowledge And Future Directions

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SPECIAL ISSUE-CURRENT EVIDENCE

Microplastic occurrence and effects in commercially harvested North American finfish and shellfish: Current knowledge and future directions

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Scientific Significance Statement

As global seafood consumption rises, it is important to understand the mechanisms by which fisheries are affected by microplastic pollution. A growing body of literature describes the occurrence and effects of microplastics in commercial species, primarily from Europe, Asia, and South America; however, there are far fewer studies conducted in North America. In this article, we review the evidence available for the presence and effects of microplastics on commercially valuable fishery species of North America and possible consequences of human consumption. We identify key priorities for future research on this topic including geographic and taxonomic representativeness; physiological, organismal, and population level effects; microplastics as multiple stressors; human health risks; and standardization of field and lab protocols.

Abstract

Commercial fisheries yield essential foods, sustain cultural practices, and provide widespread employment around the globe. Commercially harvested species face a myriad of anthropogenic threats including degraded habitats, changing climate, overharvest, and pollution. Microplastics are pollutants of increasing concern, which are pervasive in the environment and can harbor or adsorb pollutants from surrounding waters. Aquatic organisms, including commercial species, encounter and ingest microplastics, but there is a paucity of data about those caught and cultured in North America. Additional research is needed to determine prevalence, physiological effects, and population-level implications of microplastics in commercial species from Canada,

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the United States, and Mexico. Investigations into possible human health effects of microplastic exposure from seafood are also greatly needed. This synthesis summarizes current knowledge, identifies data gaps, and provides future research directions for addressing microplastics effects in commercially valuable North American fishery species.

Commercial fisheries and aquaculture in North America serve as cornerstones for many communities with deep roots in subsistence, recreational, and commercial fishing. These sectors support cultural practices and provide widespread employment throughout the continent (FAO 2018). Commercially harvested species are facing a myriad of threats in the Anthropocene, ranging from increasing ocean temperatures to modified habitats, pollution, and marine debris (Halpern et al. 2015; Lusher 2015; Hare et al. 2016; DeCourten et al. 2019). Interactions with marine debris are deeply problematic for marine species such as turtles, seabirds, marine mammals, and fishes (Wilcox et al. 2016, 2018), with entanglement and ingestion documented to cause harm at the individual and possibly population levels (Kühn et al. 2015). Plastic marine debris poses varied threats to individual organisms as well as entire food webs based on size, chemical composition, and bioavailability (Fig. 1; Gall and Thompson 2015). Microplastics, synthetic polymeric particles or fibers 0.0001–5 mm in length are an emerging area of study because they are ingested and respired by hundreds of different marine and aquatic species (Rochman et al. 2016). Numerous studies have documented effects of microplastic internalization ranging from sublethal responses such as reduced fecundity, altered growth, and increased stress to mortality at higher particle concentrations (e.g., Rochman et al. 2013, 2014; Mazurais et al. 2015; Critchell and Hoogenboom 2018).

Research is needed to determine effects and to assess the risk of microplastic ingestion and exposure on the commercially important species that are integral to the livelihoods and cultural histories of many North American communities. This synthesis of current evidence up until 01 March 2019 focuses on Canada, the U.S., and Mexico, though we acknowledge the importance of the fisheries and need for microplastic research in other countries and territories in this broad geographic region. We present the top commercial fishery species by North American country (Fig. 2; Supporting Information Appendix 1), display and describe which species have existing data on microplastics contamination and/or effects (Fig. 3, Table 1), and identify priority research areas to better understand ecological and human health risks of microplastics in North American commercial fishery species.

Commercial fisheries in North America

As of 2016, 88% of global aquaculture and fisheries production was utilized for human consumption (FAO 2018). Commercial fisheries in North America are no exception, with recent estimates for annual per capita seafood consumption at 22.6 kg, 7.3 kg, and 3.6 kg for Canada, the United States (U.S.), and Mexico, respectively (FAO 2014; Cantoral et al. 2017; National Marine Fisheries Service 2018*a*,*b*). In 2016, Canadian commercial marine and freshwater fisheries landed 0.88 million metric tons (1 million metric tons = Mt) for a total value of $2.56 billion USD ($3.37 billion CAD), with aquaculture accounting for an additional $1.02 billion USD ($1.34 billion CAD). The industry labor force in Canada includes 44,000 commercial fish harvesters and crew, 3,300 individuals employed by the aquaculture industry, and an additional 28,700 individuals in the seafood product preparation and packaging sectors (DFO 2018). U.S. fisheries landings for the same year were 4.49 Mt and exceeded $5.4 billion USD in value (National Marine Fisheries Service 2017). In 2016, these efforts were supported by over 1.2 million jobs in the U.S. (National Marine Fisheries Service 2018*a*,*b*). Between 2006 and 2014, the coastal states of Mexico produced 1.3 Mt of fish and seafood per year (85% from wild caught fishery landings; 15% from aquaculture), with an average annual economic value of $890 million USD ($17 billion MXN), and supported roughly 238,000 and 56,000 jobs, respectively, in the fishing and aquaculture sectors (Melgoza-Rocha et al. 2018). These numbers highlight the economic and cultural importance of this sector. The use of commercial seafood for fresh, frozen, canned, and cured products is integral to the economies of all three North American countries and the reliance on commercial fisheries, both wild-caught and aquacultured, for protein is predicted to increase substantially over the next few decades (World Bank 2013).

Aquaculture

Over 50% of global seafood consumption is derived from aquaculture production, with an increase to 62% of global consumption predicted by 2030 (World Bank 2013; FAO 2018). North America is currently a minor player on this global aquaculture stage, accounting for less than 1% of global production in 2014, a contribution that has steadily declined over the last two decades (FAO 2016), but with a forecasted increase in the coming decades. Aquaculture in North America is dominated by finfish production with a smaller segment dedicated to production of bivalve molluscan shellfish, predominantly oyster, clam, and mussel species (Fig. 2; Supporting Information Appendix 1). Atlantic salmon (*Salmo salar*) and rainbow trout (*Oncorhynchus mykiss*) are the chief finfish species farmed in Canada (FAO 2018) whereas Channel catfish (*Ictalurus punctatus*), rainbow trout, and Atlantic salmon are the leading finfish produced by U.S. aquaculture (National Marine Fisheries Service 2018*a*,*b*). In 2014, finfish

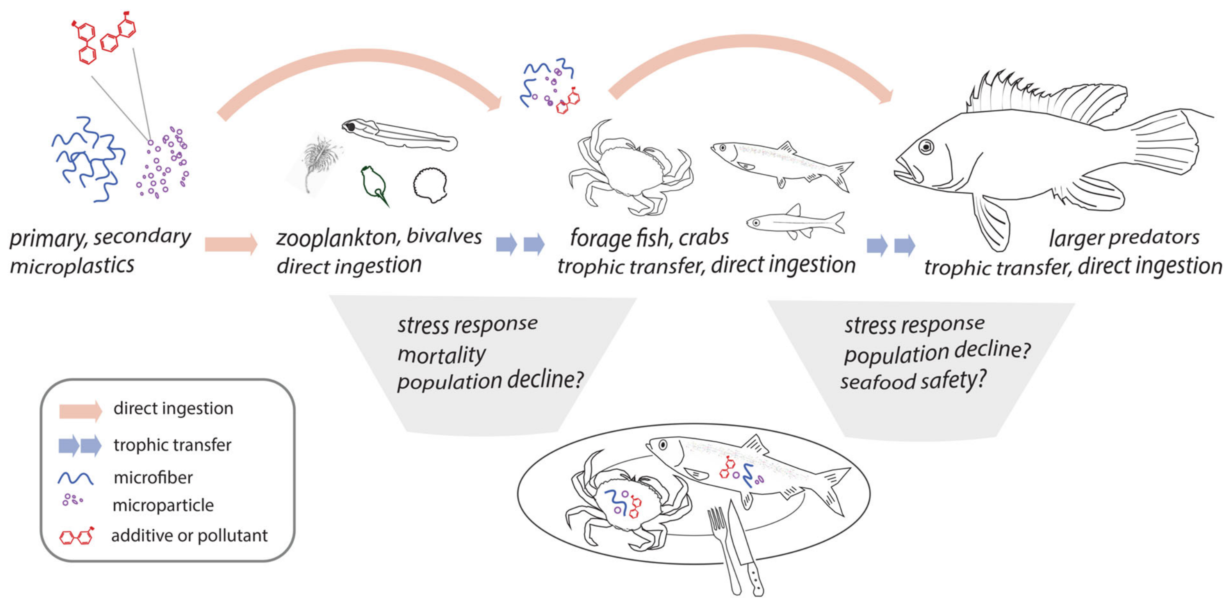

Fig. 1. Microplastics from primary and secondary sources enter the food chain by direct ingestion at all trophic levels, but are also acquired in prey items and hence may bioaccumulate in larger organisms, causing negative health effects that may impact population persistence. Ultimately microplastics and associated additives or sorbed pollutants may threaten the safety of seafood ingested by humans.

aquaculture in Mexico was dominated by production of tilapia, carp, and trout varieties (Fig. 2; Supporting Information Appendix 1; Melgoza-Rocha et al. 2018).

The primary species used in shellfish aquaculture varies by North American country (Supporting Information Appendix 1). In Canada, the most valuable cultured shellfish fisheries on both the Atlantic and Pacific coasts are mussels (*Mytilus edulis*), oysters (*Crassostrea virginica*, *C. gigas*), clams (Manila clam *Venerupis philippinarum*, soft-shell clam *Mya arenaria*, geoduck *Panopea generosa*, quahog *Mercenaria mercenaria*, littleneck clam *Protothaca staminea*, varnish clam *Nuttallia obscurata*), and scallops (Supporting Information Appendix 1). In 2017, while mussels were the largest farmed shellfish fishery by landing weight in Canada (0.024 Mt), oysters were the most valuable fishery at $33.93 million USD ($45.12 million CAD; Supporting Information Appendix 1). In 2016, the year with the most recent U.S. aquaculture data, U.S. shellfish aquaculture yielded 0.017 Mt of oysters ($192 million USD), 0.005 Mt of clams ($138 million USD), and 0.002 Mt of shrimp ($10 million USD; National Marine Fisheries Service 2018*a*,*b*). In Mexico, farmed bivalve species include the blue mussel, hard clams, oysters (*C. virginica*, *C. gigas*, *C. corteziensis*, *Pteria sterna*, *Pinctada mazatlanica*), and scallops. The Eastern oyster is the most heavily cultured bivalve in the Gulf of Mexico and is sold for both human consumption and adornments using its pearls and shells (National Aquaculture Sector Overview 2018; Tunnell 2017).

No crustacean aquaculture farms currently exist in Canada; however, across the U.S. and Mexico, brown, white, and pink shrimp (*Farfantepenaeus aztecus*, *Litopenaeus setiferus*, *Farfantepenaeus duorarum*) are the primary crustaceans farmed (FAO 2018). Most of this industry is located on the Gulf Coast of Mexico, primarily in Louisiana, Alabama, and Texas in the U.S. and into the Gulf Coast of Mexico. Mexico's shrimp aquaculture recorded 0.056 Mt in 2003 (National Aquaculture Sector Overview 2018). Although aquacultured species represent a relatively small fraction of seafood produced and consumed in North America, a substantial presence as well as predictions of increased production makes this market important for the consideration of potential microplastic effects.

Wild harvest

Though North America is not a top global producer of aquacultured seafood, the region is a significant contributor to global marine finfish landings (Supporting Information Appendix 1; FAO 2018). Among the three countries, the U.S. has the highest landings and is ranked 3rd globally for total marine capture, having produced 3.96 Mt in 2017. Canada reported 0.43 Mt in commercial finfish landings for 2017 with Pacific salmon (*Oncorhynchus* spp.), herring (*Clupea* spp.), hake (*Merluccius* spp.), redfish (*Sebastes* spp.), and cod the most frequently landed (Fisheries and Oceans Canada 2018). In the U.S., the top species by landed weight were Alaskan pollock (*Gadus chalcogrammus*), menhaden (*Brevoortia* spp.), Pacific salmon (*Oncorhynchus* spp.), hake, and cod (*Gadus* spp.; *see* Fig. 2, Supporting Information Appendix 1; National Marine Fisheries Service 2018*a*,*b*). Just over 1.0 Mt of commercial finfish were landed in Mexico where Pacific sardines (*Sardinops sagax*), tuna (various spp.), tilapia (various spp.), anchoveta (*Cetengraulis mysticetus*), and carp (various spp.) were among the most captured in 2014 (Melgoza-Rocha et al. 2018; most recent data available).

Like finfish, shellfish (including crustaceans, bivalves, and other molluscs) are important players in North American coastal ecosystems, cultures, economies, and diets. Dozens of species are harvested from the wild in Canada, the U.S., and Mexico (Supporting Information Appendix 1). In Canada, crabs (*Cancer magister*, *Chionoecetes opilio*, *C. bairdi*) and lobster (*Homarus americanus*) comprise the bulk of wild-caught shellfish production, totaling roughly 0.10 Mt landed for each respective fishery in 2017 (Fig. 2; Supporting Information Appendix 1; Fisheries and Oceans Canada 2018). Wild Atlantic prawn (*Pandalus borealis*), a coldwater shrimp, has historically been one of the most important commercial harvests off the east coast of Canada, however as of 2018, NOAA reports this fishery collapsed (National Marine Fisheries Service 2018*a*, *b*). Along the Gulf of Mexico, there are 49 officially recognized shellfish species harvested, with 16 species collected from U.S. waters, and 46 harvested from Mexican waters (Tunnell 2017). In the U.S., shrimp, squid, crabs (*Cancer magister*, *Callinectes sapidus*, *Chionoecetes opilio*, *C. bairdi*), and lobster (*Homarus americanus*) were the highest-volume, highest-value fisheries in 2017 (Fig. 2; Supporting Information Appendix 1; National Marine Fisheries Service 2018*a*,*b*). Shrimp, oysters, squid, and crab were the most significant shellfisheries in Mexico in 2014, the most recent year for which landings data are available (Supporting Information Appendix 1), though differences between wild-caught and farmed fisheries are difficult to parse out (Melgoza-Rocha et al. 2018). Fisheries along the Gulf of Mexico coastline continue to fluctuate in response to natural and anthropogenic distrurbances (Tunnell 2017) and fishery data are likely underreported (Finkbeiner and Basurto 2015). Overall, the continued strength of these wild fisheries is critical to the economies of all three countries, thus emerging anthropogenic effects such as those presented by microplastics are of considerable concern. While this paper does not focus on wild fisheries for subsistence by tribal and other entities, it is also critical to consider the importance of these wild resources through this lens. Based on these data, the relevant species for studying microplastics in North American commercial fisheries vary regionally but with some species groups in common—an important consideration when targeting and designing future studies.

Marine microplastics: A brief review

Marine anthropogenic debris, primarily in the form of plastics, is ubiquitous and persistent, and comprises up to 95% of all waste in global oceans and on beaches (Andrady 2011; Eriksen et al. 2014; Galgani et al. 2015). The amount of plastic entering the marine environment continues to increase annually and it is estimated that in 2010 alone, 4.8–12.7 Mt of plastic ended up as marine litter, representing 1.7–4.6% of the total plastic waste generated in 192 coastal countries (Jambeck et al. 2015). Microplastics, 0.0001–5 mm in size, have been documented throughout the water column, in surface waters, sediments, and in marine organisms and are therefore a global threat to marine ecosystems (Barnes et al. 2009; Avio et al. 2017). Although widespread, distribution of microplastics in coastal and marine environments is unpredictable and patchy because meteorological, atmospheric, coastal, and tidal processes all contribute to the movement, dispersal, and accumulation of these largely buoyant particles (Foekema et al. 2013). However, the microplastics problem is particularly pronounced in coastal zones due to their proximity to terrestrial inputs, tidal processes that provide favorable conditions for debris accumulation (Ryan et al. 2009; Weinstein et al. 2016; Gray et al. 2018), wave action, and UV light exposure that collectively promote fragmentation (Andrady 2011). The risks of microplastic exposure to coastal fisheries and aquaculture in North America are not well defined.

Not only is plastic found widely in the marine environment, it is also ingested by hundreds of species around the world, spanning freshwater, coastal, pelagic, demersal, benthic, as well as deep-sea environments (Rochman et al. 2015; Alomar and Deudero 2017; Jamieson et al. 2019). A 2015 meta-analysis by Gall and Thompson indicated that over 690 species have reported encounters with marine debris through entanglement and ingestion, with 92% of those encounters involving plastic. Over 220 species of marine organisms, ranging from microscopic zooplankton to bivalves, fish, marine mammals, sea turtles, sharks, seabirds, and a host of other marine-associated species, have been documented to ingest plastics (Lusher et al. 2017). The majority of microplastic pollution research in North America has sought to determine environmental concentrations of microplastics in lakes, rivers, estuaries, and sediments, with recent investigations of municipal wastewater treatment plants (WWTPs) as potential avenues for microplastics to enter aquatic ecosystems (Auta et al. 2017; Gies et al. 2018). For example, Mason et al. (2016) reported the average concentration of microplastics in WWTP effluent across the United States as 0.05 ± 0.024 particles L^{-1}. Freshwater ecosystems in North America were also found to have an abundance of microplastics. Eriksen et al. (2013) reported microplastic concentrations in the Great Lakes of: 1277–12,645 particles km^{-2} in Lake Superior, 0–6541 particles km^{-2} in Lake Huron, and 4686–466,305 particles km^{-2} in Lake Erie. Microplastics are also present in North American lake sediments with 140–980 items kg^{-1} dry sediment recorded for Lake Ontario (Ballent et al. 2016). Microplastic concentrations in North American river water and sediments have been reported across a wide range. For example, the San Gabriel and Los Angeles Rivers of California contained 411 particles m^{-3} and 12,932 particles m^{-3} of water, respectively (Moore et al. 2011). Notably, microplastic levels in the waters of the North Shore Channel in Chicago, Illinois, U.S., downstream from a WWTP, were measured at 17.93 ± 11.05 particles m^{-3} (McCormik et al.2014; Shahul Hamid et al. 2018) and in the St. Lawrence River in Canada were $13{,}832 \pm 13{,}677$ particles m^{-2} of sediment (Castañeda et al. 2014). These data provide evidence that waterways act as both sinks of some microplastic pollution as well as sources of microplastic pollution to marine systems.

Below, we review existing data on microplastics in North American fisheries species current to 01 March 2019, and outline the needs and future directions for the study of occurrence and effects of microplastics in commercially harvested finfish, bivalves, and crustaceans in this part of the world. We offer suggestions for future laboratory and field studies related to commercial fisheries in Canada, the U.S., and Mexico.

Ecological prevalence and effects

The primary route of organismal microplastic exposure occurs via ingestion of microplastics mistaken for natural prey items (Lusher 2015), or ingestion of contaminated prey items (Nelms et al. 2018), though both finfish and shellfish can also passively uptake microplastics through respiration and via the gills (Watts et al. 2015). Consumed microplastics can transfer across trophic levels and may bioaccumulate in predators (Farrell and Nelson 2013; Setälä et al. 2014). Plastic materials identified in the digestive tracts of marine organisms include fibers, foams, films, and fragments with recorded chemical signatures of cellophane, high density polyethylene (HDPE), low density polyethylene (LDPE), polyethylene terephthalate (PET, PETE), nylon (PA), polypropylene (PP), polymethylmethacrylate (PMMA), polyurethane (PU, PUR), polystyrene (PS), among others determined by various spectroscopic techniques such as Fourier-transform infrared (FTIR) and Raman spectroscopy (Hidalgo-Ruz et al. 2012; Wagner et al. 2017; Pinto da Costa et al. 2019). Microfibers are the most prevalent category of microplastics ingested by marine fishes, crustaceans, and bivalves, typically representing more than 90% of plastics ingested (Mizraji et al. 2017), with microplastic fragments, foams, and films representing a smaller proportion (Jabeen et al. 2017).

Additives and monomers, including bisphenol A (BPA), organotoxins, and phthalates, with established biologically harmful properties such as reproductive toxicity, mutagenicity, and carcinogenicity, are used to manufacture plastics (Teuten et al. 2009). If microplastics are ingested, these compounds can be released from the polymer and absorbed by predators (Browne et al. 2008, 2013). In addition to containing additives, plastics also adsorb harmful hydrophobic persistent organic pollutants (POPs) such as dichlorodiphenyltrichloroethane (DDT), polychlorinated biphenyls, polycyclic aromatic hydrocarbons, polybrominated diphenyl ethers, and dioxins, among others (Rios et al. 2007; Bakir et al. 2014; Gallo et al. 2018). Because of their high surface area to volume ratio and hydrophobic nature, microplastics are known to sorb hydrophobic organic pollutants in concentrations up to 1 million times greater than surrounding waters (Mato et al. 2001). Under physiological conditions, these pollutants may desorb into the digestive tracts of animal predators when ingested. The ability of plastics to sorb to chemicals that can become bioavailable is a concern attributed to microplastic consumption, although studies are ongoing to determine whether leaching from ingested plastics significantly increases contaminant burden. However, the endocrine disrupting properties of these hydrophobic and persistent chemicals in wildlife are well documented, as well as the ability of such chemicals to cause sublethal effects on growth, reproduction, and behavior at very low concentrations (e.g., ng L^{-1}) (reviewed in Colborn and Thayer 2000; Brander 2013). As such, the leaching of even small amounts of these pollutants from ingested plastic may pose an additional hazard to marine organisms. Furthermore, internal migration of plastic particles has been documented in fish and crabs in laboratory studies that report smaller microparticles translocated internally to the circulatory system and tissues (e.g., liver, hepatopancreas) in a range of taxa (Browne et al. 2008; Avio et al. 2015; Brennecke et al. 2015). In the model zebrafish, microplastics can be maternally transferred to eggs (Pitt et al. 2018). Translocation of microplastics may make leaching of associated chemicals more likely.

Marine species, including those harvested for commercial purposes, may therefore be ingesting both plastic debris and a cocktail of associated contaminants (Rochman et al. 2015). Laboratory studies have demonstrated that continuous exposure to contaminated plastics can lead to accumulation of plastic-associated pollutants in fish tissue in as little as 21 d (Rochman et al. 2013; Wardrop et al. 2016).

Human exposure and effects

Given the prevalence of microplastics in coastal environments, it is not surprising that they have been detected in seafood intended for human consumption (Van Cauwenberghe and Janssen 2014; Rochman et al. 2015). Shellfish, small fish (e.g., herring, anchovies), bivalves, and echinoderms may pose the greatest risks to human consumers because they are usually eaten whole, including the gastrointestinal tracts and/or gills which are known sites of microplastic accumulation (Smith et al. 2018). Microplastic exposure in humans remains understudied. Only one report to date has examined human feces finding that samples contained up to nine different types of plastic, with PP and PET being most common. This provides preliminary insights regarding microplastic exposure and ingestion by humans (Liebmann et al. 2018). Environmental exposure to microplastics can occur through inhalation or ingestion, with endocytotic and paracellular transfer across epithelial tissues proposed as mechanisms for uptake into human blood and tissues (Wright and Kelly 2017). The average person is estimated to ingest more than 5,800 plastic particles combined annually from beer, water, and sea salt (Kosuth et al. 2018), compared with an estimated annual exposure of 11,000 and 110,000 particles for seafood consumers in Europe and China, respectively (Van Cauwenberghe and Janssen 2014; Li et al. 2015). Even though 90% of ingested microplastics are thought to be removed from the human body through the excretory system (EFSA Panel on Contaminants in the Food Chain 2016), particles either retained or excreted may have human health implications. Adverse effects include inflammatory responses, transfer of sorbed pollutants, and disturbance of the gut microbiome (Wright and Kelly 2017). For example, both PE (0.5–50 μm) and PET (0.5–20 μm) particles derived from the wear and tear of plastic prosthetic implants are found to migrate to cells and tissues and cause increased inflammatory response (Willert et al. 1996). Specifically, PE particles are found to accumulate in lymph nodes and to stimulate an immune response (Morawski et al. 1995; Bitar and Parvizi 2015). As in marine fauna, plastic additives and unreacted monomers may leach out once microplastics enter the human body.

Human health effects of many POPs, some plastic additives, and selected monomers such as styrene are well established. For example, high levels of BPA in human urine, ranging from 1 to 8 ng mL^{-1}, has been linked to cardiovascular disease, Type 2 diabetes, higher odds of obesity, and abnormal waist circumference (Lang et al. 2008; Do et al. 2017). Phthalates elicit endocrine disrupting properties at certain concentrations; vinyl chloride, acrylonitrile, acrylamide, and ethylene oxide monomers can cause mutagenicity, carcinogenicity, and toxicity and are associated with birth defects such as hypospadias (altered male urethra placement; Halden 2010; Lithner et al. 2011; Rochester 2013); and POPs are long documented to increase adverse health effects (Carpenter 2011). Microplastics may also alter the microbiome of the tissues they interact with and can potentially be carriers of pathogens through the microbial communities found on their surface (Wright and Kelly 2017). Considering the physical disruption and potential risk of translocation, as well as chemical additives, sorbed pollutants, and microbes associated with microplastic particles, there is a valid concern for potential human health effects due to microplastic ingestion. Only by more thoroughly quantifying the presence of microplastics in organisms consumed as seafood can we begin to properly assess both the levels of exposure and the risk associated with their consumption.

Microplastics in commercial fisheries

Finfish

The majority of microplastics research has focused on organisms in European, Asian, or South American waters (Barboza et al. 2018). However, a number of publications have reported the occurrence of microplastics in commercially valuable species of North America, focusing primarily on the presence or absence of microplastics within the fishes' gastrointestinal tracts (Fig. 3, Table 1). The limited number of studies conducted in North America (e.g., British Columbia, Newfoundland, and Saskatchewan in Canada; California, Connecticut, and Texas in the U.S.) indicate the presence of microplastics in field-collected finfish from freshwater bodies, coastal environments, and associated watersheds (e.g., Phillips and Bonner 2015; Liboiron et al. 2016; Collicutt et al. 2019, Fig. 3, Table 1). Studies by Carpenter et al. (1972), Phillips and Bonner (2015), Liboiron et al. (2016), Campbell et al. (2017), Munno (2017), Peters et al. (2017), and Liboiron et al. (2018) document the presence of microplastics in field-collected commercial finfish, and Rochman et al. (2015) reported the presence of anthropogenic debris in eight species of commercial finfish purchased from local markets being sold for human consumption (Table 1). The reported ingestion of microplastics varies widely for finfish sampled from North American waters, ranging from 0% in individual silver hake (*Merluccius bilinearis*) to 46.5% in individual pinfish (*Lagodon rhomboides*) to 83% in individual northern pike (*Esox lucius*; Campbell et al. 2017; Peters et al. 2017; Liboiron et al. 2018). This suggests that microplastic ingestion may be largely influenced by the areas surrounding the sampling location, indicated by the higher incidence of plastics in fishes from more urbanized areas (Phillips and Bonner 2015; Liboiron et al. 2016; Campbell et al. 2017). For example, Hipfner et al. (2018) documented the presence of microfibers in 21% of individual Pacific herring (*Clupea pallasii*) from the highly urbanized Salish Sea; but no microfibers were detected in herring collected from remote locations along the British Columbia coast. Similarly, European commercial fishes sampled from the North Sea and the English Channel demonstrated an overall microplastic ingestion of 2.6% and 36.5%, respectively (Foekema et al. 2013; Lusher et al. 2013). The inter- and intraspecies variation in plastic ingestion, as well as the amount, morphology, and polymer type of microplastics ingested by freshwater and marine commercial finfish raise important questions. Different feeding strategies among species as well as the heterogeneous distribution of plastics in the environment likely account for some of these observations (Lusher et al. 2017; Peters et al. 2017). Plastic ingestion in fishes occurs across a wide variety of feeding types or guilds, and this grouping may offer important insights on predicting microplastic accumulation in fish (Vendel et al. 2017; McNeish et al. 2018). One recent study in Mexico investigating microplastic burden in herbivorous (*Scarthychthys viridis*), omnivorous (*Girella laevifrons*), and carnivorous (*Graus nigra*, *Helcogramoides chilensis*, *Auchenionchus microcirrhis*) fishes found that omnivores had significantly higher microplastic loads in their guts than the other two feeding groups (Mizraji et al. 2017). Fibers are consistently documented as the leading form of ingested microplastic by wild-caught specimens with PE, PP, and polyamide (PA) among the most commonly identified microplastic polymers ingested by marine organisms (Lusher et al. 2013; Rummel et al. 2016).

The physiological ramifications of microplastic ingestion in commercially valuable finfishes are not well studied in North American species. To our knowledge, there are only two published North American-based laboratory studies, which aim to determine ingestion or retention of microplastics in Atlantic menhaden, pinfish, striped mullet (*Mugil cephalus*), spot (*Leiostomus xanthurus*), flounder (*Paralichthys* spp.) and rainbow trout (Munno 2017, Table 1). Additional laboratory studies involving model species—zebrafish (*Danio rerio)*, common goby (*Pomatoschistus microps*), and Japanese medaka (*Oryzias* *latipes*)—along with Crucian carp (*Carassius carassius*), salmon, pike, and rockfish (*Sebastes schlegelii*) have demonstrated the potential for microplastic accumulation in organismal tissues, including the translocation of microplastics from the gastrointestinal tract into hepatic tissues (Lu et al. 2016). Effects include oxidative and hepatic stress, modified predatory behaviors, reduced energy reserves, decreased lipid metabolism, and the potential for endocrine disruption (Cedervall et al. 2012; Rochman et al. 2014; de Sá et al. 2015; Lu et al. 2016; Yin et al. 2018). The reported physiological effects associated with microplastic exposure in finfish can vary widely. For example, the European sea bass (*Dicentrarchus labrax*), a commercial species in the Mediterranean Sea, exhibited pathological alterations to its intestinal epithelium following a 30–90 d exposure to untreated and polluted PVC microplastic pellets, suggesting that microplastics and POPs can have a significant negative effect on fish health (Pedà et al. 2016). Conversely, minimal effects were observed following a short-term exposure to microplastics in the same species (Mazurais et al. 2015). Such variation may be due to differences in experimental design of laboratory exposures including choice of microplastic types and concentrations, exposure periods, and measured endpoints (de Sá et al. 2018).

Shellfish

Microplastic research in shellfish has been primarily conducted in Europe and Asia with relatively little research on commercially harvested shellfish occurring in North America. To date, bivalves are the most well-represented commercial fishery group in the field of microplastics research due to their sessile nature, filter or suspension feeding modes, and ecological, economic, and cultural importance. Blue mussels (*Mytilus edulis*) are sediment-dwelling, model organisms for microplastic studies and are frequently used in the laboratory setting (Van Cauwenberghe et al. 2015). Studies on field-collected shellfish in North America (e.g., British Columbia, New Brunswick and Nova Scotia in Canada; East and South Coasts—Maine, Connecticut, North Carolina, South Carolina and Florida, and West Coast-Oregon and California in the U.S.) indicate the presence of microplastics in tissues of mussels, oysters, clams, scallops, and lobster from estuarine and coastal environments (e.g., Mathalon and Hill 2014; Murphy 2018; Waite et al. 2018; Baechler et al. this issue, Figs. 2, 3; Table 1), with at least one study comparing farm-raised and wild-caught organisms and finding no significant difference in microplastic burden between the two groups (Davidson and Dudas 2016). Studies by Mathalon and Hill (2014), Davidson and Dudas (2016), Murphy (2018), Waite et al. (2018), Zhao et al. (2018), Potocka et al. (2019), and Baechler et al. (this issue) document presence of microplastics in field-collected bivalves but do not include laboratory exposure studies (Table 1). To our knowledge, there have only been six North American-based laboratory studies published, which aim to determine the propensities of shellfish to intake or egest microplastics (Table 1). These studies demonstrate uptake of microplastic beads, pellets, and fibers in oysters, clams, scallops, and mussels (Brillant and MacDonald 2000; Ward and Kach 2009; Wertz 2018; Woods et al. 2018), and indicate microplastic accumulation may vary by organ. For example, Gaspar et al. (2018) documented accumulation of plastic nanobead particles in the hepatopancreas of American oysters, a high value commercial species (Fig. 2; Table 1). Laboratory studies on shellfish undertaken outside of the North American continent report mixed physiological effects and biological endpoints in bivalves exposed to microplastics of varied types, sizes, and materials (Santillo et al. 2017). However, several types of microplastics (microparticles, microbeads, microfibers) can cause increased respiration rates, changes in feeding, reduced fecundity, DNA damage, and neurotoxicity in various species (e.g., Green 2016; Sussarellu et al. 2016; Ribeiro et al. 2017; Woods et al. 2018). Specifically, polyethylene microbeads 0–80 μm diameter have been shown to induce tissue inflammation in the blue mussel (von Moos et al. 2012), and those 2–6 μm interfere with energy uptake, reduce oocyte number, larval yield, and larval development in the Pacific oyster (Sussarellu et al. 2016). PS microgranules (63–250 μm) reduce energy intake in the beach clam *Atactodea striata* (Xu et al. 2017). Laboratory studies show direct ingestion of PS microbeads (3 and 10 μm diameter) in bivalves (Browne et al. 2008) as well as trophic transfer of 0.5 μm diameter microbeads from bivalve prey to crustacean predators (Farrell and Nelson 2013), transport of 0–80 μm diameter microbeads through the digestive system (von Moos et al. 2012), and accumulation of 50 nm and 3 μm PS microbeads in tissues (Gaspar et al. 2018). Kolandhasamy et al. (2018) also demonstrated that blue mussels incorporate microfibers (> 100 μm) into various organs including those not associated with the digestive system (e.g., foot, mantle), suggesting direct contact could lead to microplastic uptake via an unknown mechanism. The ability of blue mussels to eliminate microfibers has been observed by allowing depuration or purging of the bivalve gut in clean filtered seawater resulting in egestion of up to 60% of ingested microfibers over 9 h (Woods et al. 2018). Research on the prevalence and effects of microplastic ingestion in commercially important crustaceans across Canada, U.S., and Mexico is extremely limited; a single study has examined the prevalence of microplastics in commercial American lobsters from the northeast U.S. (Supporting Information Appendix 1). No data currently exist for most commercially important crustaceans, including snow crab, Dungeness crab, blue crab, and shrimp (*Farfantepenaeus aztecu*—brown, *Litopenaeus setiferus*—white, and *Farfantepenaeus duorarum*—pink) as well as a number of other North American commercially important species including abalone (*Haliotis rufescens*), conch (*Stombus*), squid (*Loligo opalescens*), and octopus (*Octopus vulgaris*).

Data gaps and future directions for North American fisheries

While research on microplastics in marine and coastal organisms is rapidly expanding and evolving, relatively little is known about the prevalence and effects of microplastics for many commercially important species. Priority goals include

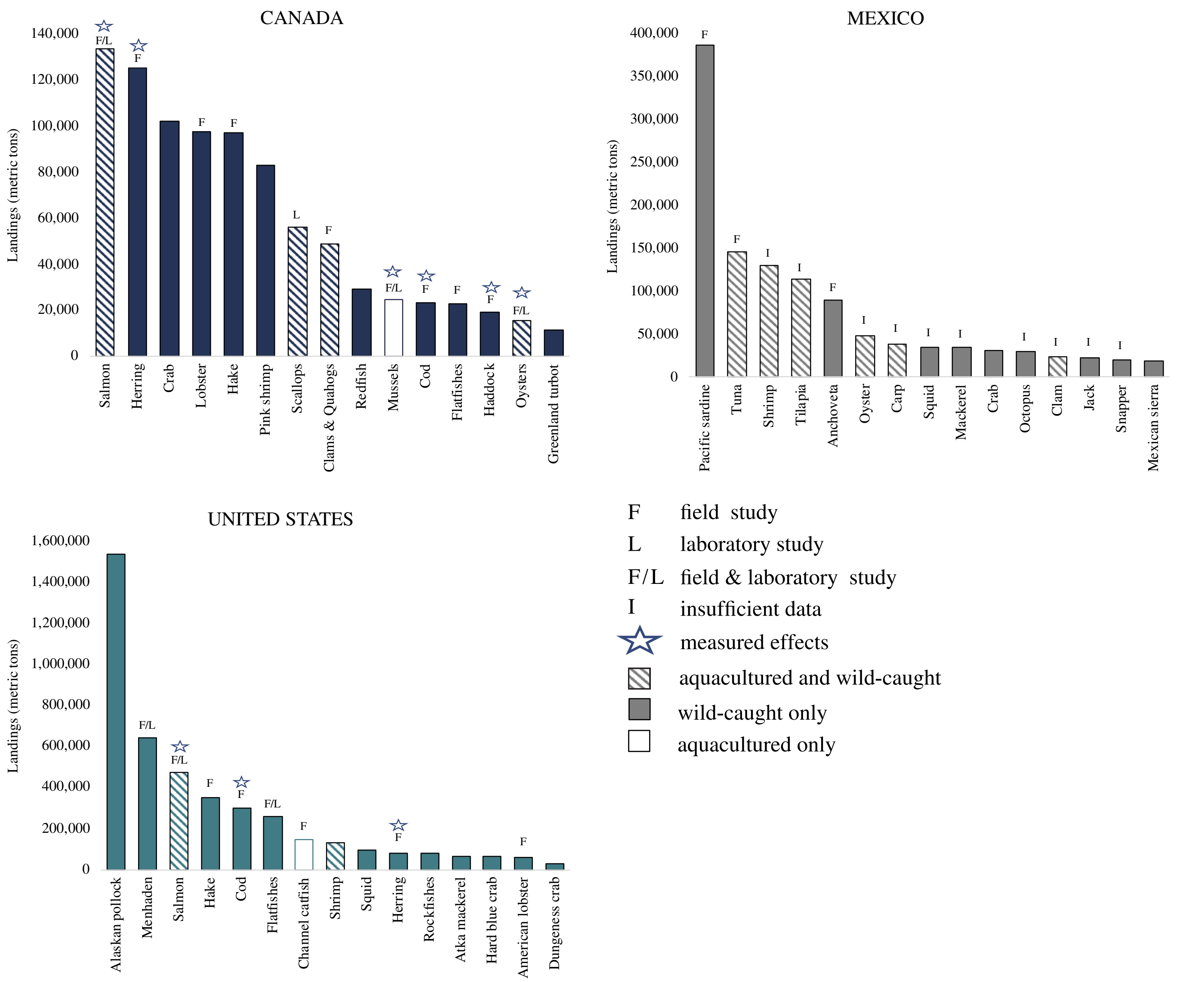

Fig. 2. Top North American Finfish and Shellfish Fisheries by landed weight in Canada, the United States, and Mexico. Hashed bars indicate a combination of wild and aquacultured fisheries; filled bars indicate wild fisheries only; white bars with no fill indicate aquacultured fisheries only. Presence of microplastics investigations in the field or laboratory anywhere in the world is indicated by F (Field study), L (laboratory study), F/L (both field and laboratory studies), or I (Insufficient landings data). A star above the bar indicates that effects of microplastics have been studied.

improving geographic representation of studies, broadening taxonomic sampling, increasing efforts to measure physiological, organismal, population- and community-level effects on target species, risk assessments for human populations that rely on these fisheries, and importantly, standardization of field and laboratory methodologies.

Geographic and taxonomic representation

To date, relatively few studies have investigated microplastic effects in commercially harvested species in North America (Table 1). The current body of published microplastic literature focuses mostly on species collected from or commercially targeted in Europe, Asia, and South America. Moreover, emphasis has been placed on species that are model organisms, easily accessible through established sampling programs, or regularly available for sale at local markets. Determining microplastic exposure and effects in a more representative pool of commercially harvested freshwater, coastal and marine fishes, crustaceans, and molluscs is critical to better understand the prevalence of microplastics in North American commercial fishery species and to further estimate potential risks. For example, the vast majority of microplastic research conducted in Mexico measures environmental concentrations of plastics in water and sediments (e.g., Retama

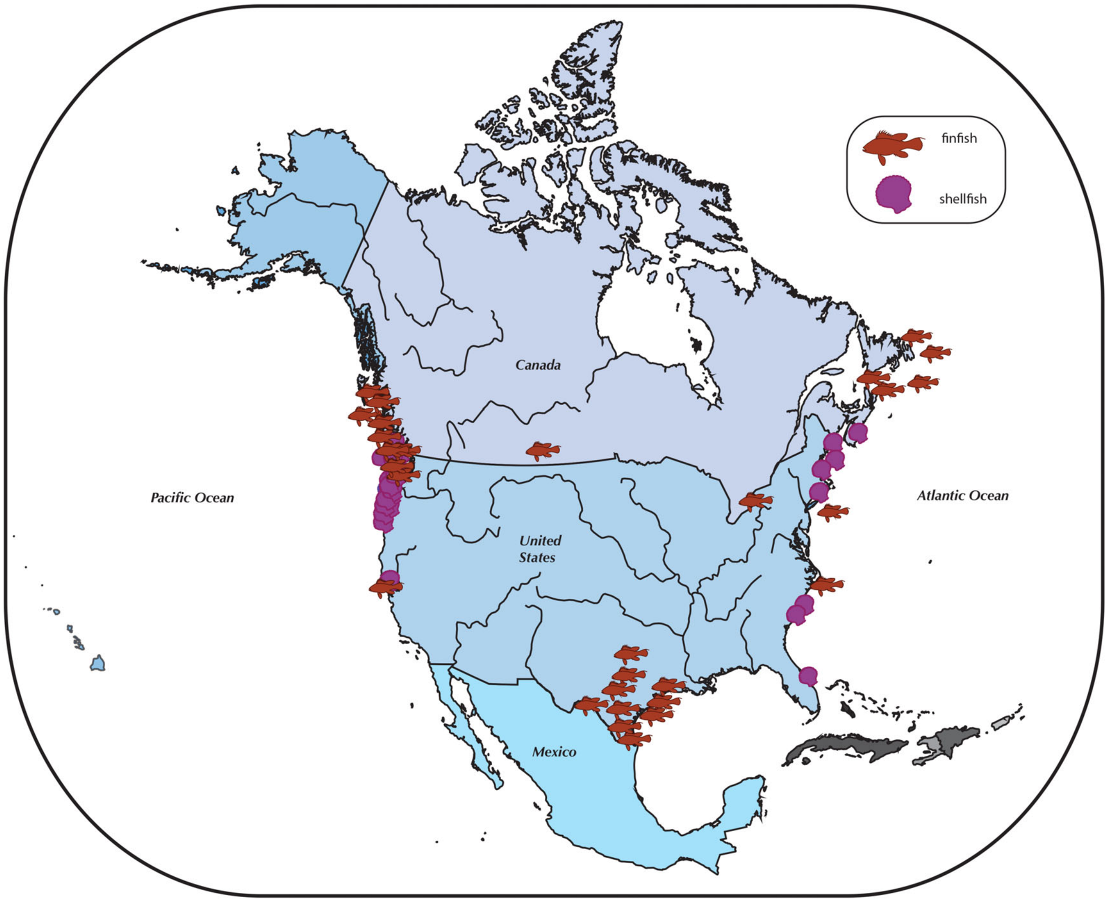

Fig. 3. North America, consisting of Canada, the United States (including Hawaii), and Mexico, is home to numerous fisheries. Shown here are the locations of studies examining microplastic occurrence in finfish (n = 11) and shellfish (n = 13) species harvested for seafood. Each point represents one site, often with multiple sites per study. All data displayed here correspond with Table 1.

et al. 2016; Di Mauro et al. 2017; de Jesus Piñon-Colin et al. 2018), but studies addressing the occurrence and effects of plastic debris in commercially harvested marine or aquatic species from Mexican waters have yet to be undertaken.

Worldwide, laboratory studies of commercial fish species are also lacking. Difficulties with live capture, animal husbandry, and inherent species-specific complications such as delicate life histories or long reproductive cycles hamper such studies. In addition, the propensity for air or water-borne microplastic contamination in an experimental setting may confound results. These challenges mean laboratory studies must be carefully planned, tightly controlled, and meticulously monitored to ensure results reflect relevant levels of microplastic contamination (Barboza et al. 2018).

Physiological effects of microplastics

Few studies have examined altered growth or other physiological effects in commercial finfish species (but see: Critchell and Hoogenboom 2018) in response to microplastic ingestion. One study reports decreased oxygen consumption of the crab *Carcinus maenas* when exposed to PS microbeads (Watts et al. 2016). Physiological studies on fish and benthic organisms have demonstrated depressed growth, increased metabolism, changes in feeding rate, and decreased reproductive output when exposed to microfibers, microbeads, and microparticles (e.g., Cedervall et al. 2012; Green 2016; Sussarellu et al. 2016; Woods et al. 2018; Athey et al. Forthcoming). However, studies that evaluate responses on the subcellular, cellular, or organ-levels following exposure to plastics are limited. Thus, a broader range of physiological endpoints across biological scales is needed to fully evaluate the toxicity of microplastics to aquatic organisms (Lusher 2015).

Organismal and population level effects of microplastics

Among a range of taxa, it is evident that microplastics could affect organism- and population-level endpoints including behavior, larval development, growth, reproduction, and physiological function in a number of commercially important North American finfish and shellfish species (e.g., Cedervall et al. 2012; Green 2016; Sussarellu et al. 2016; Ribeiro et al. 2017; Woods et al. 2018), thus impacting fisheries health in the long term. The available literature focuses primarily on responses of individuals to microplastics without evaluating effects on populations or food webs (Lusher et al. 2017). This is likely due to the difficulties of implementing population-level studies in the environment (i.e., lack of control in the natural environment, time and resource-intensive nature of the work required, and the multitude of other environmental stressors at a site). While laboratory studies using high microplastic doses provide useful physiological insights, it is difficult to scale those results to the population-level in order to determine environmental effects (Burns and Boxall 2018).

Further research and modeling efforts examining population-, community-, and ecosystem-level effects of microplastics using environmentally relevant concentrations and commercially and/or ecologically important species are needed. Future studies should investigate mechanisms of microplastic uptake, anatomical burdens of internal microplastics, microplastic egestion and excretion rates, and physiological effects of microplastics on various levels of biological organization (from the subcellular to cellular, anatomical, and individual), such as the approach taken with other pollutants (e.g., Brander et al. 2015; Ankley et al. 2010). Such research will aid fisheries and aquaculture managers in their ability to predict potential population-level issues associated with increased exposure to microplastics in the environment as human population and plastic consumption continue to rise.

Microplastics as one of multiple stressors

Research on the effects of microplastic exposure has focused on specific physiological or biological responses in isolation. We know that marine organisms are exposed to multiple stressors in their environment with the potential for additive or synergistic effects (Noyes and Lema 2015; DeCourten and Brander 2017). Yet how microplastics are interacting with other environmental stressors such as hypoxia, increased ocean temperatures, and ocean acidification, and whether such interactions lead to additive or synergistic effects in commercially important North American fishery species is another demonstrable data gap.

Unknown human health risks

Primary concern regarding ingestion of polluted microplastics by commercial fishery species is the food web biomagnification of microplastics (Derraik 2002; Moore 2008; Teuten et al. 2009). The bioavailability of micro and nanoplastics and associated contaminants within tissues of commercial species caught and sold for human consumption may pose health risks to human consumers. Most studies examining the ecotoxicology of microplastics use microplastics spiked with analogs (congeners; Hermabessiereet al. 2017) rather than the environmentally relevant suite of potentially harmful chemical additives and monomers or variety of sorbed pollutants from the environment. Therefore, the human health risks from consumption of microplastic-affected commercial species are unknown. Furthermore, in the environment, commercial species experience prolonged exposure to microplastics and the suite of associated toxic chemicals, yet the vast majority of exposure studies are of short duration, spanning 21 (Wardrop et al. 2016) to 60 d (Rochman et al. 2013).

Standardization of field and laboratory protocols

Recent reviews have highlighted the importance of microplastic type in laboratory studies (Paul-Pont et al. 2018). Microfibers are the most common form of microplastic ingested by wild-caught fisheries species, but few studies have focused on the effects of microfiber ingestion. Controlled laboratory microfiber feeding studies documenting uptake rates and physiological effects in commercially important species are extremely limited in number, with only one study in North America specifically focused on microfiber uptake (Table 1; Woods et al. 2018). There is a need to increase study of microfiber toxicity specifically, and broaden the microplastic types used in laboratory studies generally. More work surrounding how material or microplastic type (e.g., natural vs. fully synthetic or polyester vs. polypropylene fiber) affect chemical leaching should also be undertaken. Additionally, there is a need for more rapid and cost-effective sample processing methods to advance our understanding of microplastic prevalence and effects across a broader range of commercial species and locales in a reasonable timeframe. Analysis of microfibers or microplastics with any dimension in the micron range requires very specific, highly technical, and costly instruments such as μ-FTIR or μ-Raman spectroscopy (Rocha-Santos and Duarte 2015; Silva et al. 2018). Current issues in analytical spectroscopy include lack of a sufficient reference database, limited number of North American laboratories processing microplastic particles, interference from plastic additives including dyes, sorbed pollutants, biological contamination, and interpretation of results for smaller particles due to low signal to noise ratio and loss of information in spectral fitting and processing. Another challenge is the ubiquitous nature of microplastics, necessitating a consistent, strict field and laboratory sampling protocol to avoid contamination from microplastics shed from clothing, equipment, and the air. The field is cognizant of the pressing need to standardize protocols for microplastic isolation and analysis to increase consistency among federal and state agencies, aquaculture staff, management agencies, and researchers, allowing for appropriate comparisons among geographic and taxonomic ranges to establish baselines for long-term monitoring.

Conclusions

The majority of microplastic literature from North America focuses on occurrence in sediments, rivers, estuaries, WWTPs, or a relatively small number of species, leaving a critical gap in our knowledge of the occurrence in and effects of microplastic ingestion in commercial fisheries. A handful of studies document presence/absence of microplastics in North American commercial fishery species, but very few have tested

Table 1. Microplastic studies on North American Commercial Finfish and Shellfish Species

Paper Title	Author	Date	Species studied	Location	Lat, Long	Microplastic/ Macroplastic/ other contaminant	Microplastic type studied or found	Field or Lab Study	Endpoint measured
Polystyrene spherules in coastal waters	Carpenter et al.	1972	Winter flounder (*Pseudopleuronectes americanus*) White perch (*Morone americana)*	Niantic Bay, Connecticut, USA	41°18′00.0"N 72°10′00.0"W	Microplastic	Nurdles, PCBs	Field	Prevelance in sea surface NE Coast, and in fish
Ingestion of plastic by teleost fishes	Hoss and Settle	1990	Atlantic menhaden (Brevoortia tyrannus), Pinfish (*Lagodon rhomboides*), Striped mullet (*Mugil cephalus*), Spot (*Leiostomus xanthurus*), Flounder (*Paralichthys* spp.)	North Carolina, USA	34°43′08.4"N 76°40′20.9"W	Microplastic	Particle	Laboratory	Laboratory studies on larvae that five of six species tested will feed on polystyrene microspheres.
Occurrence and amount of microplastic ingested by fishes in watersheds of the Gulf of Mexico	Phillips and Bonner	2015	**44 freshwater species; 8 marine species evaluated**Dolphinfish *(Coryphaena hippurus*), Southern Flounder (*Paralichthys lethostigma*), Blue Tilapia (*Oreochromis aureus*), Spotted Sea Trout (*Cynoscion nebulosus*), Red drum (*Sciaenops ocellatus*), Pinfish (*Lagodon rhomboides*), Mangrove Snapper *(Lutjanus griseus*), Red Snapper (*Lutjanus campechanus*), Largemouth Bass (*Micropterus salmoides*), Channel Catfish *(Ictalurus punctatus*), Gulf Menhaden (*Brevoortia patronus*)	Gulf of Mexico estuary and freshwater drainages (Neches River, San Antonio River, Rio Grande, Red River, Brazos River, Colorado River, Nueces River, Laguna Madre), USA	29°58′07.7"N 93°51′20.5"W; 28°54′56.5"N 97°47′36.0"W; 29°33′18.4"N 101°15′04.6"W; 33°41′17.4"N 96°20′19.9"W; 31°34′41.7"N 97°08′54.4"W; 30°40′02.8"N 98°26′30.5"W; 27°50′16.2"N 97°29′18.0"W; 26°41′38.7"N 97°25′41.3"W	Microplastic	Filament, fragment, film	Field	Among 535 fishes examined in study, 8% occurrence of microplastics in freshwater fishes and 10% in marine fishes. Plastic types included polyester, polystyrene, polypropylene, acrylate, and nylon. In non-urbanized streams, occurrence of microplastics ingested by fish (5%) was less than in an urbanized stream (Neches River; 29%).
Anthropogenic debris in seafood: Plastic debris and fibers from textiles in fish and bivalves sold for human consumption	Rochman et al.	2015	Jacksmelt (*Atherinopsis californiensi*), Pacific anchovy (*Engraulis mordax*), Yellowtail rockfish (*Sebastes flavidus*), Striped bass (*Morone saxatilis*), Chinook salmon (*Oncorhynchus tshawytscha*), Blue	Markets from California (Half Moon Bay and Pillar Point Harbor), USA	37°30′07.4"N 122°28′56.1"W; 37°28′46.6"N 122°27′49.3"W	Microplastic (anthropogenic debris)	Fiber	Field	In Indonesia, anthropogenic debris was found in 28% of individual fish and in 55% of all species. In the USA, anthropogenic debris was found in 25% of individual fish and in 67% of all species.

(Continues)

Table 1. Continued

Paper Title	Author	Date	Species studied	Location	Lat, Long	Microplastic/ Macroplastic/ other contaminant	Microplastic type studied or found	Field or Lab Study	Endpoint measured
			rockfish (*Sebastes mystinus*), Pacific sanddab (*Citharichthys sordidus*), Lingcod (*Ophiodon elongatus*)						
Low plastic ingestion rate in Atlantic cod (*Gadus morhua*) from Newfoundland destined for human consumption collected through citizen science methods	Liboiron et al.	2016	Atlantic cod (*Gadus morhua*)	Newfoundland (Petty Harbour and St. Phillip's Harbour), Canada	47°27′51.2"N 52°42′22.2"W; 47°35′34.9"N 52°53′13.7"W	Microplastic	Thread (not fiber), film, fragment	Field	Plastic ingestion rate of 2.4% for Atlantic cod (n = 205). This plastic ingestion prevalence rate is among the lowest recorded to date. Used citizen science to collect GI tracts from fish destined for human consumption. First recorded baseline for fish in Newfoundland, Canada
Microplastics in the gastrointestinal tracts of fish and the water from an urban prairie creek	Campbell et al.	2017	Northern pike (*Esox lucius*)	Saskatchewan (Wascana Creek), Canada	50°26′21.9"N 104°37′49.1"W	Microplastic	Fiber, fragment	Field	Quantified the number of microplastics in a prairie creek immediately downstream of Regina, Saskatchewan, Canada. At least one microplastic was detected in 73.5% of fish and 95.6% of water samples, showing that the creek and reliant fauna contain microplastics.
Microplastic Retention by Type in Several Species of Fish from the Great Lakes	Munno (Master's thesis)	2017	Rainbow trout (Oncorhynchus mykiss)	Ontario, Canada	43°42′27.8"N 79°23′41.7"W	Microplastic	Particle	Laboratory	Rainbow trout retained 95% of ingested polystyrene beads within the gastrointestinal tract after 24 hours post-ingestion
Foraging preferences influence microplastic ingestion by six marine fish species from the Texas Gulf Coast	Peters et al.	2017	Atlantic croaker (Micropogonias undulatus)Pinfish (Lagodon rhomboides)	Galveston Bay to Freeport (Gulf of Mexico), USA	29°28′19.2"N 94°46′09.1"W; 28°57′14.8"N 95°21′34.9"W	Microplastic	Fibers and particles	Field	Studied six marine fish species from the Texas Gulf Coast. Analyzed 1381 fish and 42.4% contained ingested microplastic, including fibers (86.4%), microbeads (12.9%), and fragments (<1.0%).

(Continues)

Table 1. Continued

Paper Title	Author	Date	Species studied	Location	Lat, Long	Microplastic/ Macroplastic/ other contaminant	Microplastic type studied or found	Field or Lab Study	Endpoint measured
Two forage fishes as potential conduits for the vertical transfer of microfibres in Northeastern Pacific Ocean food webs	Hipfner et al.	2018	Pacific herring (Clupea pallasii)	British Columbia (Lucy Island, Moore Island, Pine Island, S'Gang Gwaay, Triangle Island), Canada & Washington (Protection Island), USA	54°17′ N 130°37′ W; 52°57′ N 129°34′ W; 50°35′ N 127°26′ W; 52°05′ N 131°13′ W; 51°52′ N 129°05′ W; 48°07′ N 122°55′ W	Microplastic	Fibers	Field	Two types of fish collected in North Sea over 8 years; 1.5% of 734 sand lance and 2.0% of 205 herring contained plastic. At-sea density of plastic and ingestion frequency were unrelated. Plastic loads were highest in the Salish Sea, which is surrounded by urban development.
A zero percent plastic ingestion rate by silver hake (Merluccius bilinearis) from the south coast of Newfoundland, Canada	Liboiron et al.	2018	Silver hake (Merluccius bilinearis)	Newfoundland (Burgeo Bank, St. Pierre Bank, Southern Grand Bank), Canada	47°06′22.7"N 58°09′11.2"W; 46°27′36.0"N 57°19′01.6"W; 44°21′28.1"N 53°29′10.7"W	Microplastic	None found	Field	Occurrence frequency of plastic ingestion is 0% for silver hake (n = 134). Findings of 0% plastic ingestion describe important fish-plastic interactions. First recorded baseline for silver hake plastic ingestion.
Microplastics in juvenile Chinook salmon and their nearshore environments on the east coast of Vancouver Island	Collicutt et al.	2019	Chinook salmon (Oncorhynchus tshawytscha)	Vancouver (Deep Bay, Big Qualicum River, Nanaimo River Estuary, Cowichan Bay), Canada	49°27′51.9"N 124°43′50.5"W; 49°23′38.4"N 124°37′04.7"W; 49°09′15.8"N 123°53′32.8"W; 48°44′32.3"N 123°37′14.2"W	Microplastic	Fibers	Field	Microfibers (100–5000 µm in length) found in juvenile chinook salmon, coast of BC Canada. Most abundant colors of the microfibers were clear (41%) and blue (20%).
Postingestive selection in the sea scallop, Placopecten magellanicus (Gmelin): the role of particle size and density	Brillant and MacDonald	2000	Sea scallop (Placopecten magellanicus)	St. Andrew's, New Brunswick, Canada	45°02′55"N, 67°02′55"W	Microplastics	Partcles	Field -collected, laboratory study	P. magellanicus is able to discriminate microplastics by particle size; retains larger particles (20 µm) for longer duration than smaller (5 µm) particles.
Marine aggregates facilitate ingestion of nanoparticles by suspension-feeding bivalves	Ward and Kach	2009	Blue mussels (Mytilus edulis) and Eastern oysters (Crassostrea virginica)	Avery point, Long Island Sound, Connecticut, USA	41°18′53.65"N 72°03′52.03"W	Microplastics	Particles	Laboratory	Nanoparticles were taken up by two species of suspension-feeding bivalves (Blue mussel and Pacific oyster), which captured individual particles <1 µm with a retention efficiency of <15%.

(Continues)

Table 1. Continued

Paper Title	Author	Date	Species studied	Location	Lat, Long	Microplastic/ Macroplastic/ other contaminant	Microplastic type studied or found	Field or Lab Study	Endpoint measured
Microplastic fibers in the intertidal ecosystem surrounding Halifax Harbor, Nova Scotia	Mathalon and Hill	2014	Blue mussel (Mytilus edulis)	Halifax Harbor, Nova Scotia, Canada	44°38′52.16"N 63°33′47.70"W	Microplastics	Fibers	Field	Enumerated microplastics in intertidal sediment, fecal matter, and Mytilus edulis. Higher concentrations were observed in farmed compared to wild mussels.
Microplastic ingestion by wild and cultured manilla clams (Verupis philippinarum) from Baynes Sound, British Columbia	Davidson and Dudas	2016	Wild and farmed manila clams (Verupis philippinarum)	Baynes Sound, BC, Canada	49°32′45.287"N 124°50′59.83"W	Microplastic	Fibers, films, and fragments	Field	Microplastics were isolated from 54 Manila clams (27 farmed and 27 wild) from three shellfish farms and three reference beaches in Baynes Sound, British Columbia, Canada. Microplastic concentrations ranged from 0.07 to 5.47 particles/g (reference beach and shellfish farms, respectively) with no significant difference in microplastic concentrations between cultured and wild clams. Fibers were the dominant microplastic (90 %); colorless and dark gray fibers (36 and 26 %, respectively) were most common.
Direct and indirect effects of different types of microplastics on freshwater prey (Corbicula fluminea) and their predator (Acipenser transmontanus)	Rochman et al.	2017	Asian clams (Corbicula fluminea)	University of California-Davis, California, USA	38°32′10.52"N 121°43′36.02"W	Microplastics and PCBs	Micronized pellets	Field-collected, laboratory study	Clams were exposed to environmentally relevant concentrations of polyethylene terephthalate (PET), polyethylene, polyvinylchloride (PVC) or polystyrene with and without polychlorinated biphenyls (PCBs) for 28 days. Their predators, white sturgeon

(Continues)

Table 1. Continued

Paper Title	Author	Date	Species studied	Location	Lat, Long	Microplastic/ Macroplastic/ other contaminant	Microplastic type studied or found	Field or Lab Study	Endpoint measured
									(Acipenser transmontanus), were exposed to clams from each treatment for 28 days. Bioaccumulation of PCBs and effects on organisms were examined across several levels of biological organization. PCBs were not detected in prey or predator, so differences in bioaccumulation among polymers and biomagnification in predators could not be measured.
Cellular Bioreactivity of Micro- and Nano-Plastic Particles in Oysters	Gaspar et al.	2018	Eastern oyster (Crassostrea virginica)	Bogue Sound, North Carolina, USA	34°42′31.09"N 76°51′40.51"W	Microplastics ingestion	Microbeads	Field-collected, laboratory study	Oysters can accumulate polystyrene (PS) beads in their tissues, especially hepatopancreatic tissues.
A Comparison of Microplastics in Farmed and Wild Shellfish nearVancouver Island and Potential Implications for Contaminant Transfer to Humans	Murphy (Masters thesis)	2018	Commercial (both wild and farmed): Blue mussel (Mytilus edulis), Manila clam (Venerupis philippinarum), and Pacific oyster (Crassostrea gigas)	Vancouver Island, BC, Canada	Farmed blue mussel:47° 9′ 28.89′′ N, 122° 59′ 21.10′′ EWild blue mussel: 48° 20′ 21.73′′ N, 123° 42′ 34.23′′ WFarmed Pacific oyster: 49° 30′ 57.93′′ N, 124° 42′ 29.61′′ WWild pacific oyster:49° 22′ 49.83′′ N, 124° 34′ 10.15′′ WFarmed Manila clams:50° 6′ 14.22′′ N, 125° 12′ 59.03′′ WWild Manila clams:50° 5′ 30.35′′ N, 125° 11′ 18.15′′ W	Microplastics	Fragments, pellets, and fibers	Field	Compared microplastic loading in three species of farmed and wild shellfish collected near Vancouver Island, BC. Significantly higher numbers of microplastics were observed in farmed blue mussels and Pacific oysters, compared to their wild counterparts. No significant difference in microplastic load was observed between farmed and wild Manila clam.

(Continues)

Table 1. Continued

Paper Title	Author	Date	Species studied	Location	Lat, Long	Microplastic/ Macroplastic/ other contaminant	Microplastic type studied or found	Field or Lab Study	Endpoint measured
Quantity and types of microplastics in the organic tissues of the eastern oyster Crassostrea virginica and Atlantic mud crab Panopeus herbstii from a Florida estuary	Waite et al.	2018	Eastern oyster (Crassostrea virginica)	Mosquito Lagoon, Florida, USA	28°45′31.83"N 80°46′33.26"W	Microplastics	Fibers, fragments	Field	Eastern oysters contained an average of 16.5 microplastic pieces/ individual. Atlantic mud crab (Panopeus herbstii) had higher microplastic concentrations per gram of tissue than oysters. Panopeus herbstii had an average of 4.2 pieces per individual in soft tissues. Royal/dark blue fibers were the most common microplastic type found.
Marine debris in Charleston Harbor: Characterizing plastic particles in the field and assessing their effects on juvenile clams (*Mercenaria mercenaria*)	Wertz (Master's thesis)	2018	Quahog clam (*Mercenaria mercenaria*)	Charleston Harbor, Charleston, South Carolina, USA	32°46′14.72" N, 79°53′48.09" W [Estimated]	Microplastics	Bead	Field-collected, laboratory study	Polyethylene spheres (10–20 μm) were fed to juvenile clams (1–2 mm) in acute (24-48 hour) and chronic (21 day) timeframes. Decreased growth recorded at highest microplastic concentration tested.
Microplastic fiber uptake, ingestion, and egestion rates in the blue mussel (*Mytilus edulis*)	Woods et al.	2018	Blue mussel (*Mytilus edulis*)	Salt Pond, Blue Hill, Maine, USA	44°22′26.1"N 68°33′36.5"W	Microplastics	Fibers	Field-collected, laboratory study	Mussels take up microplastic fibers (MPF) in a quantifiable and predictable manner. Most MPF resided in the digestive gland, with fewer in the gill. MPF were lost through pseudofeces and feces, with 60% of body load gone in nine hours.
Field-Based Evidence for Microplastic in Marine Aggregates and Mussels: Implications for Trophic Transfer	Zhao et al.	2018	Blue mussel (*Mytilus edulis*)	Groton, Connecticut, USA	41°18′53.96"N 72°03′48.18"W	Microplastics	Particles	Field	Blue mussels studied at Avery Point, Connecticut, USA; >40% of microplastic particles were rejected in pseudofeces or egested in feces.

(Continues)

Table 1. Continued

Paper Title	Author	Date	Species studied	Location	Lat, Long	Microplastic/ Macroplastic/ other contaminant	Microplastic type studied or found	Field or Lab Study	Endpoint measured
Plastic pollution affects American lobsters, *Homarus americanus*	Potocka et al.	2019	American lobster (*Homarus americanus*)	Gulf of Maine, Casco Bay area (Portland, Maine, USA)	43°41′38.66"N 69°59′40.50"W	Macroplastics	Particles	Field	First evidence of ingested plastics in American lobster. Plastic particles found in lobster stomachs were identified as rubber band pieces.
Microplastic Concentrations in Two Oregon Bivalve Species: Spatial, Temporal, and Species Variability	Baechler et al.	in review (this issue)	Pacific razor clam (*Siliqua patula*), Pacific oyster (*Crassostrea gigas*)	Oregon, USA (15 sites)	Razor clam sites (oyster grower locations witheld): 46°11′42.15″ N, 123°59′38.31 W45°54′12.84″ N, 123°58′9:63 W45°29′57.62″ N, 123°57′45.64 W44°39′36.49″ N, 124°3′40.2″ W44°36′06.21″ N, 124°04′04.99″ W43°35′78.98″ N, 124°33′02.34″ W43°20′43.22″ N, 124°20′56.55″ W43°12′44.42″ N, 124°23′48.01″ W42°27′15.78″ N, 124°25′35.12″ W	Microplastics	Fibers (>99%), Films, Foams, Fragments, Other (<1%)	Field	Microplastic prevalence: Pacific oysters from six estuaries contained 10.95 ± 0.77 microplastics and Pacific razor clams from open coast beach sites contained 8.84 ± 0.45 microplastics (contamination not subtracted); 99% were colorless, blue, gray, or black microfibers (62%, 21%, 7% and 4%, respectively). Spring-collected Pacific oysters contained more microplastics than summer samples (Spring: 13.74 ± 1.16 microplastics/organism; Summer: 8.16 ± 0.88 microplastics/organism).

microplastics as stressors or toxic agents. Of the top 10 commercial finfish species (by landed weight) in Canada, the U.S., and Mexico, microplastic occurrence has been studied in eight and effects in five Canadian species. In the U.S., occurrence has been studied in eight organisms but effects have been examined in only three, with no studies on the species with the highest U.S. landings, Alaskan Pollock. Only three of the top 10 commercial finfish from Mexico have been examined for microplastics. Among the top 10 commercial shellfish species by country, microplastic occurrence has been studied in five and effects studied in only two Canadian species; and four U.S. shellfish species have been investigated for microplastic occurrence, with effects studied in only one. To the best of our knowledge, there have been no microplastic prevalence or effect studies on Dungeness crab, snow crab, hard blue crab, surf clams, or commercially important shrimp species in North America. No microplastics data are available on commercial shellfish species from Mexico, but it should be noted that 9 of 10 species were not defined by our source data so species-specific microplastic studies could not be determined (Fig. 2; Supporting Information Appendix 1). Many commercial fisheries discussed in this article are also targeted through subsistence or tribal harvest. Given the important role of seafood in the North American diet and culture, there is an urgent need for microplastics research to better understand potential risks that microplastics and associated pollutants pose to both the fisheries and human consumers. Research priorities include: improving the geographic and taxonomic representation of commercial fishery species studied, addressing the extensive knowledge gaps in population and community level effects, and investigating microplastics as one of multiple environmental stressors. Standardization of field and laboratory protocols will facilitate advancement of knowledge in these areas. Equally important is understanding potential human health risks posed by fishery species contaminated with microplastics. These data are needed to inform policy and management decisions to reduce plastic transmission into the ocean. Ultimately, such information may lead manufacturers as well as the greater public to better understand the outcomes of personal and consumer choices around plastic use and the resultant contamination of the seafood we put on our tables; this improved understanding has the potential to promote behavioral changes in consumer choices that reduce use of these harmful pollutants and decrease incorporation of plastics into marine and coastal food webs.

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