Science of the Total Environment 733 (2020) 139381

Contents lists available at ScienceDirect

Science of the Total Environment

journal homepage: www.elsevier.com/locate/scitotenv

A Horizon Scan of research priorities to inform policies aimed at reducing the harm of plastic pollution to biota

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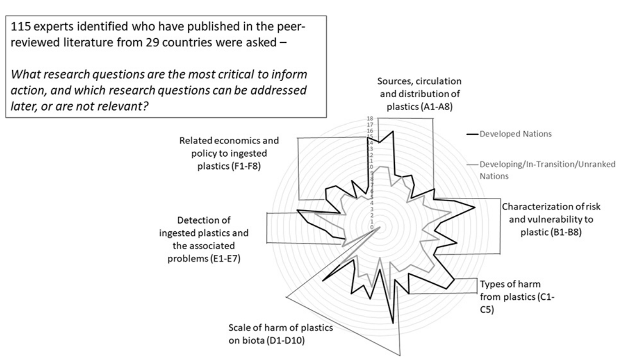
HIGHLIGHTS

- Plastic pollution is an emerging environmental pollutant.
- It is important for research to be inform policies aimed at reducing plastic pollution.
- Expert opinion was used to understand global research priorities.
- Top priorities include understanding sources and most effective policy tools.
- Priorities as determined by expert opinion show differences across several regions.

GRAPHICAL ABSTRACT



ARTICLE INFO

Article history:
Received 18 March 2020
Received in revised form 2 May 2020
Accepted 10 May 2020
Available online 13 May 2020

Editor: Jay Gan

ABSTRACT

Plastic pollution in the oceans is a priority environmental issue. The recent increase in research on the topic, coupled with growing public awareness, has catalyzed policymakers around the world to identify and implement solutions that minimize the harm caused by plastic pollution. To aid and coordinate these efforts, we surveyed experts with scientific experience identified through their peer-reviewed publications. We asked experts about the most pressing research questions relating to how biota interact with plastic pollution that in turn can inform policy decisions and research agendas to best contribute to understanding and reducing the harm of plastic

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https://doi.org/10.1016/j.scitotenv.2020.139381

Keywords:
Expert opinion
Marine debris
Plastic pollution
Policy
Prioritization

pollution to biota. We used a modified Horizon Scan method that first used a subgroup of experts to generate 46 research questions on aquatic biota and plastics, and then conducted an online survey of researchers globally to prioritize questions in terms of their importance to inform policy development. One hundred and fifteen experts from 29 countries ranked research questions in six themes. The questions were ranked by urgency, indicating which research should be addressed immediately, which can be addressed later, and which are of limited relevance to inform action on plastics as an environmental pollutant. We found that questions relating to the following four themes were the most commonly top-ranked research priorities: (*i*) *sources, circulation and distribution of plastics*, (ii) *type of harm from plastics*, (*iii*) *detection of ingested plastics and the associated problems*, and (*iv*) *related economies and policy to ingested plastics*. While there are many research questions on the topic of impacts of plastic pollution on biota that could be funded and investigated, our results focus collective priorities in terms of research that experts believe will inform effective policy and on-the-ground conservation.

1. Introduction

The occurrence and potential negative impacts of plastic pollution have been reported for over half a century (Carpenter et al., 1972; Provencher et al., 2017; Rochman, 2018; Ryan, 2015). Research and public interest have grown rapidly in recent years because of the increasing visibility of the issue in the media following the exponential increase in plastic production. To inform policy-makers of effective policies that address plastic pollution, research is needed that addresses policy-relevant, and action-orientated questions (Sutherland and Woodroof, 2009).

Plastic pollution has been found in environmental and biological samples around the globe from pole to pole, and oceans in between (Barnes et al., 2009; Lusher et al., 2015; van Franeker and Bell, 1988). It is found in a variety of habitats and environments from the deep sea to coral reefs (Anastasopoulou et al., 2013; Hall et al., 2015; Taylor et al., 2016). It is also commonly reported in freshwater and terrestrial environments, demonstrating its widespread contamination of the planet (Andrade et al., 2019; Biginagwa et al., 2016; Huerta Lwanga et al., 2017). Addressing the input of plastics into the environment is of critical urgency to reduce the current and future impacts on biota; however, there is a risk that the policies that aim to do so are misaligned with the evidence generated by the research community. Therefore, there is a critical need to coordinate plastic pollution-related research priorities and direct research funding towards answering the most pressing research questions to inform policymakers. Horizon scanning is one approach to identify the most pressing questions, which capitalizes on the collective body of expert knowledge to 'systematically search for potential threats and opportunities that are currently poorly recognized' (Sutherland and Woodroof, 2009).

Plastic pollution is associated with various perceived and/or demonstrated threats. Below, we describe entanglement and ingestion. Entanglement in plastic pollution is also a concern for many wildlife species. Whales, seabirds, turtles, and fish may become entangled in plastic pollution, which often leads to injury or death (Gregory, 2009; Kühn et al., 2015). Plastic entanglement can be caused by small items such as plastic bags, to large aggregations of synthetic fishing gear that is lost or discarded at sea.

The ingestion of plastics can have several negative impacts on biota. Larger macroplastics (>100 mm) down to microplastics (<5 mm) can block or damage gastrointestinal tracts (Pierce et al., 2004; Ryan, 1988), negatively affect physical condition (Lavers et al., 2019, 2014), increase levels of toxic contaminants (Lavers and Bond, 2016; Ryan et al., 1988; Tanaka et al., 2019), and in some cases cause death (Drever et al., 2018; Jacobsen et al., 2010; Wilcox et al., 2018). Demonstrated population-level impacts from plastic ingestion in biota are sparse (Law, 2017; Rochman et al., 2016). However, sub-lethal effects have been reported in some species (e.g. Lavers et al., 2019), and there is some evidence of effects at the population and community levels (Green, 2016; Sussarellu et al., 2016). Modelling approaches have shown that it is likely that individuals from all seabird species have ingested at least some plastic as of 2018, including 135 species that have never been studied, and 16 species where >50 individuals have been sampled, but no plastic has yet been found (Avery-Gomm, 2020). While one review has found that plastic ingestion by fish is a global occurrence (Azevedo-Santos et al., 2019), another review found that nearly half of all fish studied do not appear to ingest plastics at all, though larger sample sizes are required (Liboiron et al., 2018). A recent study examining 21 fish species in Australian waters only detected plastic in one individual (Cannon et al., 2016). The differences in these studies highlight that the frequency of occurrence of ingested plastics can vary dramatically among species and locations, and therefore indicate how a better understanding of the ways plastic ingestion affects species, populations and communities is of critical importance for conservation efforts. With more coordinated research efforts, our understanding of the potential of population-level impacts will only improve (Avery-Gomm et al., 2018; Law, 2017).

In addition to the deleterious physical effects, plastic ingestion can result in exposure to chemical and microbial agents (e.g. Arias-Andres et al., 2019; Jacquin et al., 2019; Ryan, 1988; Tanaka et al., 2015). Chemicals including trace elements, brominated flame retardants, and legacy organochlorines can accumulate on the surface of plastic particles and then may be desorbed during digestion and absorbed by the organism's digestive tract (e.g. Chua et al., 2014; Lavers and Bond, 2016; Prunier et al., 2019; Tanaka et al., 2015; Zhang et al., 2015). In other cases, chemicals used in the plastics themselves may be released during digestion, including phthalates and UV stabilizers (Hermabessiere et al., 2017; Lu et al., 2019; Tanaka et al., 2019). In general, the chemical effects of plastic ingestion are much less studied than the physical effects, and the potential toxicological impacts on various biota are not well understood.

Plastic pollution does not obey geopolitical boundaries and can originate from distant locations (Carlton et al., 2018; Obbard, 2018) or local sources (Lebreton and Andrady, 2019; Ryan et al., 2019), requiring international cooperation and accountability (Borrelle et al., 2017). The tensions between global and regional or local priorities for plastic pollution and regional plastic pollution profiles are fundamentally different and may result in conflicting priorities. For example, sites closer to plastic sources like fishing activity or human development are more likely to be polluted (Benjamins et al., 2011; Bond et al., 2012; Bråte et al., 2018; Liboiron et al., 2019), and research and policy requirements likely need to focus on these components of plastic pollution. Similarly, relationships among researchers, priorities under funding calls, and desires to engage with local communities can influence where monitoring and research efforts are undertaken, and this likely bias the information that is available.

In response to public concerns about plastic pollution, new policies and initiatives have been proposed and implemented, including legislative bans on single-use plastics (UNEP, 2019) and coordinated efforts at the regional and international level, such as the #CleanSeas initiative (https://www.cleanseas.org/), and the Basel Convention (www.basel.int/).

Our study capitalizes on the collective body of expert knowledge and critical understanding of the impacts of plastic pollution on biota within a diverse research community to prioritize research questions that will help inform policies relating to plastic pollution in the environment. Specifically, we identify research questions focused on actions and policies that will help reduce plastics and biotic interactions, building on work by Vegter et al. (2014), who used a group of experts to identify global research priorities to mitigate the impacts on wildlife and habitats from plastics. We expand on this approach by asking which research questions relating to plastic pollution and biota should be addressed, and which are of limited relevance to inform actions to mitigate plastics as an environmental pollutant. Even though only 6 years have elapsed between these two studies, the field of plastic pollution research has expanded rapidly (Provencher et al., 2017). Consequently, research priorities can shift quickly. Importantly, we discuss our identified priorities in relation to each other and how they will inform action and rank research priorities in relation to each other to help prioritize areas of research and funding.

2. Methods

We used a modified Horizon Scan approach (Sutherland and Woodroof, 2009) to elicit expert opinion in a wide community of experts on the topic of marine plastic pollution and biota. Briefly, the Horizon Scan approach uses a group of recognized experts to generate a list of emerging research questions through a series of discussions of the topic and goal. It is important to solicit a variety of experts to identify and prioritize research questions and synthesize the results to overcome individual expert context, beliefs, and personal biases (Burgman, 2016). Therefore, in addition to the Horizon Scan strategy popularised by Sutherland and Woodroof (2009), we used a two-step process for this study to ensure diverse perspectives were included in the groups of experts solicited. We aimed to get a diverse representation in the selection of a co-author group that included a range of gender, age, career stages, nationalities, and discipline expertise. The co-author group was put together from our extended professional networks and includes 60% women and non-binary members, 40% early career (within 5 years of receiving their PhD or last degree), and eight countries of origin/work from five continents. Author backgrounds and professional training included natural history, biology, ecology, environmental and chemical toxicology, and survey development and all authors are actively engaged in research in the field of plastic pollution in the environment (all would have been captured by step two, below). While this diversity is neither exhaustive nor representative, it was meant to avoid over-representing specific viewpoints.

The second step was then to solicit a wider set of experts based on publications on the topic of plastic pollution. This was done by soliciting input from all authors of English-language papers in a corpus of peer-reviewed publications, ensuring our expert pool directly replicated the existing diversity of experts in the field. This type of process is important in documenting expert opinion on topics when the methodology includes a large variety of expert types and, therefore, participants (Burgman, 2016). We employed this method to assess an expert community's opinion on how we should prioritize research questions in the plastic pollution research discipline that would best inform policy decisions to mitigate this global problem.

2.1. Research priority development

Each contributing author ($n = 14$) was asked to list seven research priorities in response to the following question in relation to plastic pollution and impacts on biota:

"*What research questions are the most critical to inform action, and which research questions can be addressed later, or are not relevant*?".

Each submitted their responses without knowing the responses of other participants. Next, four of the contributing authors (ML, JL, PR, RY) independently categorized all responses into thematic groups based on keywords and topics. These research priority lists were then discussed together and compared by a fifth co-author (JP) who grouped and summarized the responses and categorizations into a single list of research themes (see survey in Supplemental Online Material [SOM]). In no particular order, themes were: A - *Sources, circulation, and distribution of plastics*, B - *Characterization of risk and vulnerability to plastic*, C - *Types of harm from plastics*, D - *Scale of harm of plastics on biota*, E - *Detection of ingested plastics and the associated problems*, and F - *Related economics and policy to ingested plastics*. The summarized list of all research questions ($n = 46$) over the six themes was then reviewed by all co-authors for quality control for coding responses and consensus.

2.2. Expert identification and recruitment

An anonymous online survey recruited a globally distributed, broad spectrum of experts on marine plastic pollution and biota. Experts were recruited from a list of authors of peer-reviewed, English-language publications about plastic and biota found by using the search terms "plastic debris", "microplastics", and "marine debris" in Web of Science covering publications up to and including 2016. Each title and abstract of the returned search results were read to confirm a match with our subject area. From the 184 resulting papers, a list of 493 authors was created as people having expertise in marine plastic and biota. This included all the authors listed on these papers but excluded co-authors of this paper. Email contact information for all 493 listed authors was then obtained from either their publications via Web of Science (where they were the corresponding author) or from their institutional websites between 30 March and 30 April 2017. Fifty-four co-authors could not be reached by email, making the total number of people that received the survey invitation 439. The expert distribution list was contacted via email on 3 April 2018 with an invitation to take part in the survey.

The survey was available for participants to access via the weblink from 3 April 2018 to 10 January 2019. This period was targeted to maximize participation from those often engaged in fieldwork, covering typical field seasons in both the southern and northern hemispheres. Surveys were accepted until 115 experts responded (for a population of 493 experts, 115 respondents provides a confidence interval of 8.01 with a confidence level of 95%). The survey was anonymous and did not collect names, email addresses, IP addresses or other identifying data.

2.3. Online survey

The base set of research priorities was disseminated using an online survey tool (LimeSurvey) that allowed respondents to rank each research question individually. Respondents were asked to indicate whether each of the 46 research areas was:

1– highly important, crucial to inform action for research and policy development. Funding and research efforts need to concentrate on these areas first.
2– important, but not crucial to inform action for research and policy development. These research questions are important, but do not need to be done first, or should wait until other questions are answered.
3– interesting, but not important to inform action for research and policy development. These questions are of interest, but they do not need to be addressed for policy or action purposes.

Table 1
Rankings of 46 plastic pollution research questions based on 115 respondents via an online survey. The top five ranked research questions (bold) are discussed in detail.

Question number	Question	Theme	Rank (1–46)
A2	What are the sources of plastics to the aquatic environment?	Sources, circulation, and distribution of plastics	1
F8	What policy tools have been successful at reducing ingested plastics in aquatic biota?	Related economics and policy to ingested plastics	2
C2	What are the chemical effects to aquatic biota from ingesting plastics?	Types of harm from plastics	3
E5	What are the best methods for implementing standardized approaches for sampling and reporting of ingested plastics?	Detection of ingested plastics and the associated problems	4
A1	Where are the areas of highest concentrations of plastics in the aquatic environment?	Sources, circulation, and distribution of plastics	5
C1	What are the physical effects to aquatic biota from ingesting plastics?	Types of harm from plastics	6
D2	How do different concentrations of plastic ingestion affect populations?	Scale of harm of plastics on biota	7
A5	What species, groups, or habitats may act as plastic 'sinks' or areas of long-term retention in the marine environment?	Sources, circulation, and distribution of plastics	8
F2	What are the costs of clean-up vs prevention of plastics in the aquatic environment?	Related economics and policy to ingested plastics	9
C5	How do impacts on aquatic biota relate to impacts to human health?	Types of harm from plastics	10
C3	Is plastic a source of chemicals to wildlife upon ingestion?	Types of harm from plastics	11
B2	What impacts do ingested plastic fibres from synthetic textiles have on biota?	Characterization of risk and vulnerability to plastic	12
D4	How do different levels of plastic entanglement affect populations?	Scale of harm of plastics on biota	13
F3	How does aquatic plastic pollution influence food security (physical and economic access to sufficient, safe, and nutritious food for all people)?	Related economics and policy to ingested plastics	14
B3	How does a particular type of plastic influence the potential negative impacts on biota (potentially at the cellular, individual or population level)?	Characterization of risk and vulnerability to plastic	15
E6	What would facilitate comparisons among studies, synthesis of data, and identification of knowledge gaps in marine plastics research?	Detection of ingested plastics and the associated problems	16
E4	What species should be the focus for developing indicator species metrics in different regions (similar to Northern Fulmars in the North Sea)?	Detection of ingested plastics and the associated problems	17
A3	How is the level of plastic pollution changing in different parts of the aquatic environment over time (surface, water column, benthic environments)?	Sources, circulation, and distribution of plastics	18
F1	What is the cost to local economies in areas with high levels of onshore plastics (i.e. tourism, clean-up, secondary entanglement)?	Related economics and policy to ingested plastics	19
D5	What levels of plastic ingestion pose lethal effects versus sub-lethal effects to different age classes, species and other factors across biota?	Scale of harm of plastics on biota	20
C4	How do nano- and ultrafine (pieces <1 mm) plastics affect aquatic biota?	Types of harm from plastics	21
D9	How is mortality data for wildlife affected by plastics best collected?	Scale of harm of plastics on biota	22
D6	How is plastic ingestion contributing to other negative health effects for biota in a cumulative or interactive way?	Scale of harm of plastics on biota	23
B6	What are the routes and levels of primary and secondary exposure to ingested plastics in food webs?	Characterization of risk and vulnerability to plastic	24
B8	What proportion of ingested plastics (e.g. nano-plastics) are we failing to account for when quantifying ingested debris in wildlife using current techniques?	Characterization of risk and vulnerability to plastic	25
B1	Are there categories/types of plastic that are preferentially ingested by some marine biota?	Characterization of risk and vulnerability to plastic	26
F7	What mitigation tools can mitigate the negative impacts to biota posed by ongoing use of synthetic textiles?	Related economics and policy to ingested plastics	27
F5	How should aquatic plastic pollution be managed as a public health issue given that many species that ingest plastics are also consumed by humans?	Related economics and policy to ingested plastics	28
D10	What is the retention time of ingested plastics in biota?	Scale of harm of plastics on biota	29
A8	What is the fate of nano- and ultrafine plastics in an animal?	Sources, circulation, and distribution of plastics	30
E3	What are the most effective methods for non-lethal sampling assessing plastic ingestion?	Detection of ingested plastics and the associated problems	31
A4	What is the distribution and retention of plastics in freshwater systems?	Sources, circulation, and distribution of plastics	32
D1	How do different concentrations of plastic ingestion affect individuals?	Scale of harm of plastics on biota	33
B4	What life history and/or behavioural traits lead to vulnerability to plastic ingestion?	Characterization of risk and vulnerability to plastic	34
E7	What tools should be developed to allow citizen scientists to contribute to data collection?	Detection of ingested plastics and the associated problems	35
B7	How does vulnerability to ingestion/entanglement of plastics change with the annual cycle and life span of biota, i.e. age, region, migration routes, etc.?	Characterization of risk and vulnerability to plastic	36
B5	What life history and/or behavioural traits lead to high levels of retained plastic ingestion?	Characterization of risk and vulnerability to plastic	37
A7	What proportion of ingested plastic debris arises directly from fishing related activities?	Sources, circulation, and distribution of plastics	38
A6	What proportion of ingested plastic debris arises directly from synthetic textiles (microfibers)?	Sources, circulation, and distribution of plastics	39
D7	How is plastic entanglement contributing to other negative health effects for biota in a cumulative or interactive way?	Scale of harm of plastics on biota	40
F6	What is the cost to fisheries regarding seafood quality due to ingested plastics in aquatic biota?	Related economics and policy to ingested plastics	41
D3	How do different levels of plastic entanglement affect individuals?	Scale of harm of plastics on biota	42
E1	How do marine plastics contribute to the movement and introduction of invasive species?	Detection of ingested plastics and the	43

Table 1 (*continued*)

Question number	Question	Theme	Rank (1–46)
		associated problems	
D8	How does the transport of plastics by megafauna (e.g., seabirds, and marine mammals) to the terrestrial environment affect terrestrial biota?	Scale of harm of plastics on biota	44
E2	What are the potential epidemiological implications of marine plastic debris when they carry introduced species and are ingested by marine biota?	Detection of ingested plastics and the associated problems	45
F4	How is aquatic plastic pollution related to climate change?	Related economics and policy to ingested plastics	46

4– not relevant. These questions are too esoteric, do not relate to the issue of ingestion of plastics or action on plastic pollution, or are otherwise outside the purview of this kind of research.
5– unsure/do not know.

The survey also included an open section for respondents to add research questions they thought were pertinent but missing from the survey:

> "*In your opinion, are there other research questions that you feel are integral to advancing our understanding of how plastic pollution potentially affects marine biota, and mitigating the effects of plastic pollution that are not covered above*?".

Lastly, the survey included optional demographic questions for survey participants about their career stage, amount of time they had been researching plastics, type of research institute, and the geographic region of their research, as these factors are known to influence expert opinions (Burgman, 2016).

Ethics for research involving human subjects was obtained from the Interdisciplinary Committee on Ethics in Human Research (ICEHR) at Memorial University (Ethics number ICEHR No. 20180548-AR). All survey participants gave informed consent to participate in the survey (see the complete survey in SOM).

2.4. Survey results

We examined the ranking data based on survey responses to understand broad patterns of which questions were highly ranked across survey respondents as well as within certain demographics. Each research question was ranked from 1 to 46 based on the percentage of responses for each of the five response categories. Proportions were compared in a hierarchical manner; response percentages for 1 (highly important) were compared first, then 2 (important), and so on, until all questions were accounted for. For example, in a group of 3 questions where question X has 75% selected as '1', and questions Y and Z have 50% selected as '1', X would be ranked highest. The greater percentage of responses selected for '2' determined a higher-ranking question between Y and Z, and so on. If a tie occurred, and both questions had equivalent response percentages for all categories, they tied for a rank. This type of tied rankings in responses did not occur for the rankings based on all survey respondents, or for respondents from developed nations. In every other category, at least two questions tied for the same rank, with tied rankings generally being more common in categories with a lower number of respondents in most of the cases (see SOM, Table A). For reporting, we numbered the prioritized research questions in the survey using an alpha-numeric system (i.e., A1–8, B1–8, etc.) with the letter representing the theme in which the question was grouped and the number representing the sequence of the question in the survey (Table 1). The numbers were arbitrarily assigned and do not reflect prioritization.

The top five ranked research priorities were examined by grouping the respondents' ranks of each question in different themes. We present the ranked priorities first by the responses from everyone who completed the online survey, where rankings from all respondents of the survey treated as one group (Table 1). Next, to assess if priorities differed among countries with differing waste treatment infrastructure, we analyzed the top five questions by United Nations Development Program (UNDP) development rankings; that is, survey respondents from "developed" countries, as compared to "developing", "in-transition", and "unranked" category countries (UN Department of Economic and Social Affairs, 2019; UNDP, 2004; Table B SOM). A radar diagram was created to compare the five top-ranked questions between these two groups. Finally, for the global research regions, we compare the five

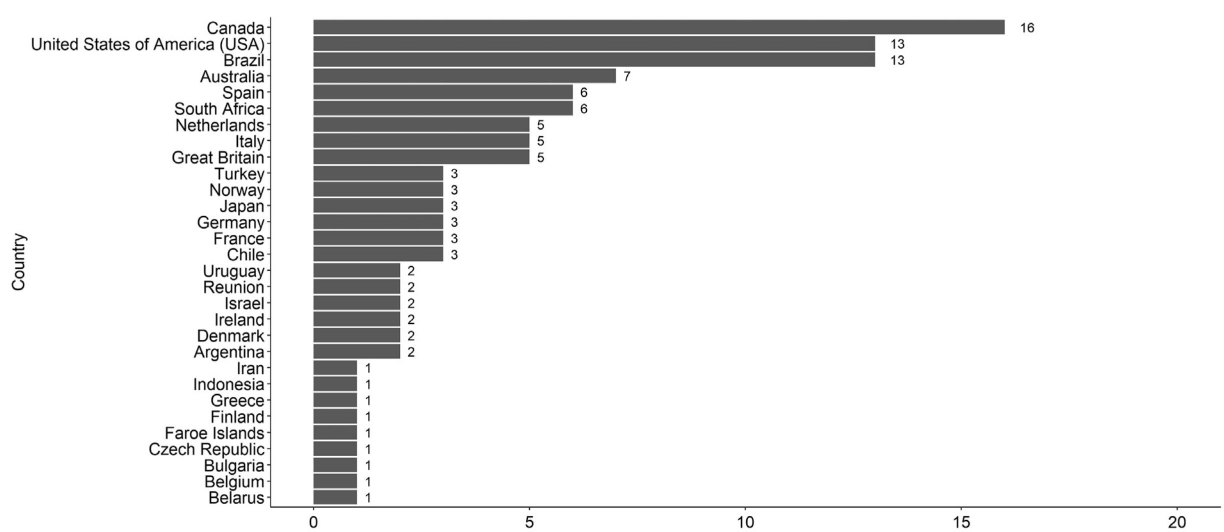

Fig. 1. Self-declared country of residence by survey respondents ($n = 115$).

top-ranked questions to examine if there are regional differences in the rankings. The map depicting the top five research questions by region was created using Microsoft Excel and R (R Development Core Team, 2017).

3. Results

A total of 115 respondents from a pool of 493 experts identified from the peer-reviewed literature completed the survey (23%; SOM). The 115 respondents represented 30 countries, with Brazil, USA and Canada yielding the greatest percentage of respondents (11%, 11% and 14% respectively; Fig. 1). The largest sector for respondents was academics, with two-thirds of survey participants identified as academics or university partners (Fig. 2). Government employed researchers were the second largest group of respondents (15%; Fig. 2). Of survey participants, 91% identified as beginning their research on aquatic plastic pollution after 2000, with 43% of all respondents beginning their plastics research between 2011 and 2015 (Fig. 3). Over two-thirds of the survey respondents ($n = 78$) were from developed nations ($n = 18$ nations), while 37 respondents were from developing, in-transition, and unranked nations ($n = 12$ nations; categories based on UNDP, 2008).

The top five research priorities aggregated for all respondents were:

1) A2: What are the sources of plastics to the aquatic environment?
2) F8: What policy tools have been successful at reducing ingested plastics in aquatic biota?
3) C2: What are the chemical effects to aquatic biota from ingesting plastics?
4) E5: What are the best methods for implementing standardized approaches for sampling and reporting of ingested plastics? and;
5) A1: Where are the areas of highest concentrations of plastics in the aquatic environment?

The top five questions for "developing", "in-transition", and "unranked" nations were:

1) A2: What are the sources of plastics to the aquatic environment?
2) A5: What species, groups, or habitats may act as plastic 'sinks' or areas of long-term retention in the marine environment?

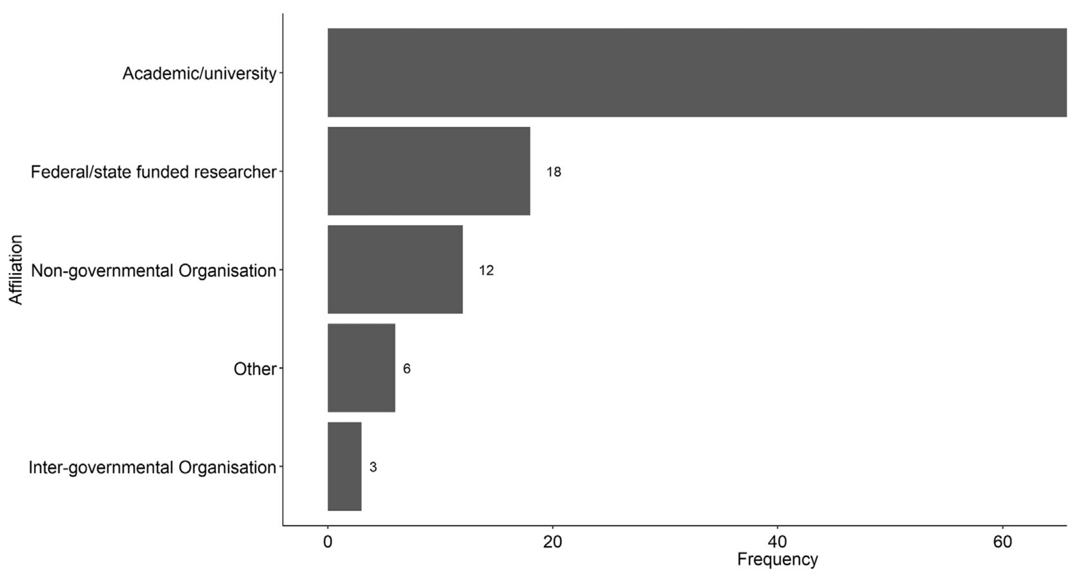

Fig. 2. Survey respondents represents a broad suite of professional affiliations, with two thirds from academic institutions (n = 115).

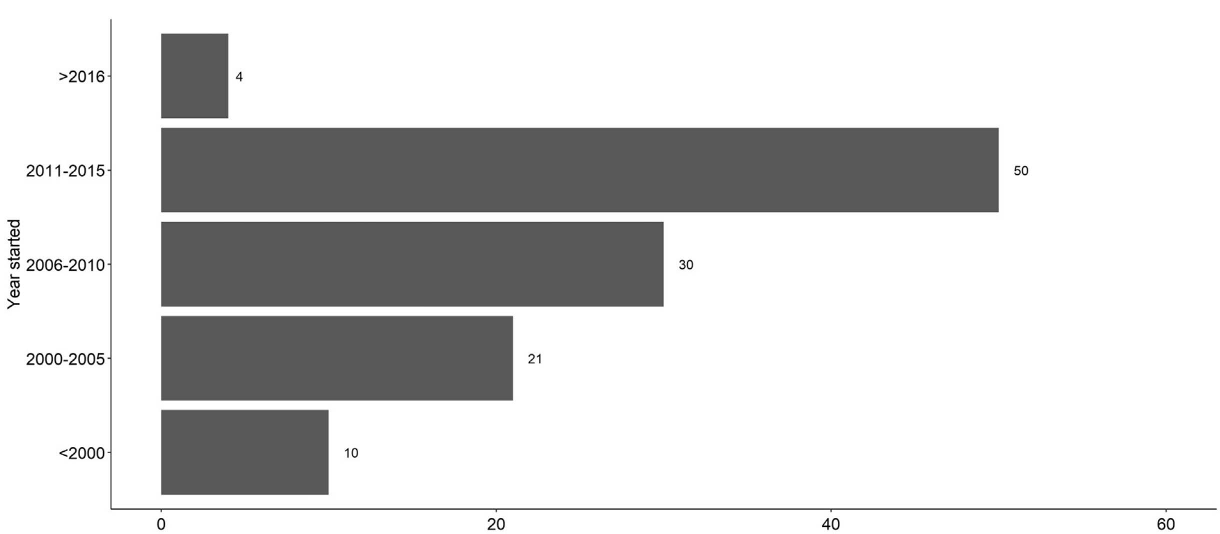

Fig. 3. Most survey respondents began researching plastics between 2006 and 2015. '2016 and later' represents 2016 to 2019 when the survey ended.

3) E5: What are the best methods for implementing standardized approaches for sampling and reporting of ingested plastics?
4) A1: Where are the areas of highest concentrations of plastics in the aquatic environment?
5) A3: How is the level of plastic pollution changing in different parts of the aquatic environment over time (surface, water column, benthic environments)?

For these respondents, theme A: *Sources, circulation and distribution of plastics* represented four of the five top-ranked research questions (Fig. 4; SOM Fig. A).

Respondents in "developed" nations identified the top five research priorities as (Fig. 4):

1) F8: What policy tools have been successful at reducing ingested plastics in aquatic biota?
2) A2: What are the sources of plastics to the aquatic environment?
3) C2: What are the chemical effects to aquatic biota from ingesting plastics?
4) E5: What are the best methods for implementing standardized approaches for sampling and reporting of ingested plastics?
5) C1: What are the physical effects to aquatic biota from ingesting plastics?

The five top-ranked research questions also differed slightly by the geographic marine region in which experts conducted their research (Fig. 5; SOM Fig. B). Research priority A2 (sources of plastics to the aquatic environment) was in the five top-ranked questions for seven of the eight regions. The next most common top-ranked question was F8 (what policy tools have been successful). Research question A1 and A5 (areas of highest concentrations and species, groups, or habitats may act as plastic 'sinks' or areas of long-term retention in the marine environment, respectively) each were in the top 5 for four regions, and the remaining research priorities were found in the top 5 of three regions or fewer. Most regions showed top-ranked questions that were a mix of the six themes (A–F), except the South Atlantic Ocean region, where experts ($n = 27$) ranked 4 of the top 5 research priorities in the *Sources, circulation and distribution of plastics* theme.

A total of 27 (23%) survey respondents indicated additional questions that should be considered to advance our understanding the effects of plastic pollution and mitigating the effects. Additional themes included understanding the most effective international forums for plastic pollution reduction policy, the need to engage with industry, effectiveness of clean-up programs, waste management, and behavioural insights studies that will focus on how the public can reduce plastic pollution (SOM; Table C). Other themes in the realm of ecology and biology included a better understanding of genetic effects of plastic pollution, trophic transfer and biomagnification of plastic pollution in food webs, the effects of plastics on bacterial communities and adequate quality assurance and quality control protocols.

4. Discussion

Policies to address the burgeoning issue of plastic pollution are under development at the international, regional, and national level (UNEP, 2019). Research objectives should be aligned with the needs of policy-makers to ensure that policies are informed by the most relevant science to manage the impacts of plastic pollution on biota, and ultimately human health, social equity, and food security (UNEA, 2017). Here, we present research questions that should be prioritized, ranked by a consortium of global experts on plastic pollution and its impacts on biota, to inform policymakers, funders, and researchers.

Perhaps surprisingly, priorities related to the vulnerability of and harm to biota from plastics were not often highly ranked by experts as critical steps to reducing the impacts of plastics on biota. Instead, research questions relating to the sources and circulation of plastics in the environment, types of harm, detection methods, and actions to reduce plastics in the environment were indicated as important by researchers to inform policy that achieves a meaningful reduction of plastics in the environment.

4.1. Highly-ranked research questions

The most often selected and highest-ranked research question by all experts was question A2, "*What are the sources of plastics to the aquatic environment*?" This suggests that a research question that experts feel needs to be addressed to reduce the impacts of plastic pollution on biota is related to where plastic pollution is released into the environment. In our interpretation, this would include obtaining better regional information on where plastics are coming from to better identify

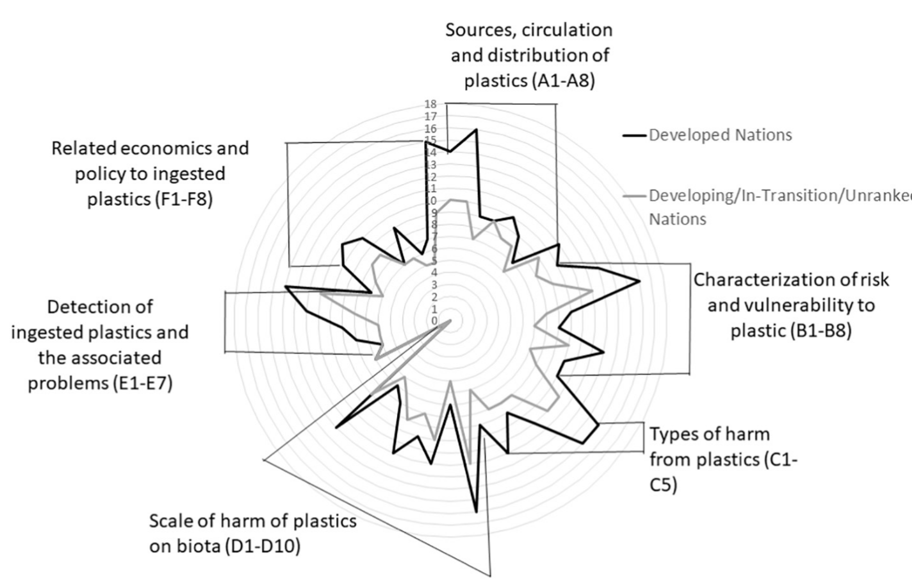

Fig. 4. Radar diagram showing the occurrence of all questions in top five research priorities for developing, in-transition, and unranked nations ($n = 11$), and developed nations ($n = 19$). Each question is represented by the peaks and valleys in the radar circle around the centre, with the scale from 0 to 18 representing how often the priority was listed by survey respondents to be in the top five questions to be addressed. The dark line represents all survey respondents from developed nations, and the gray line represents all survey respondents from developing/in-transition-unranked nations.

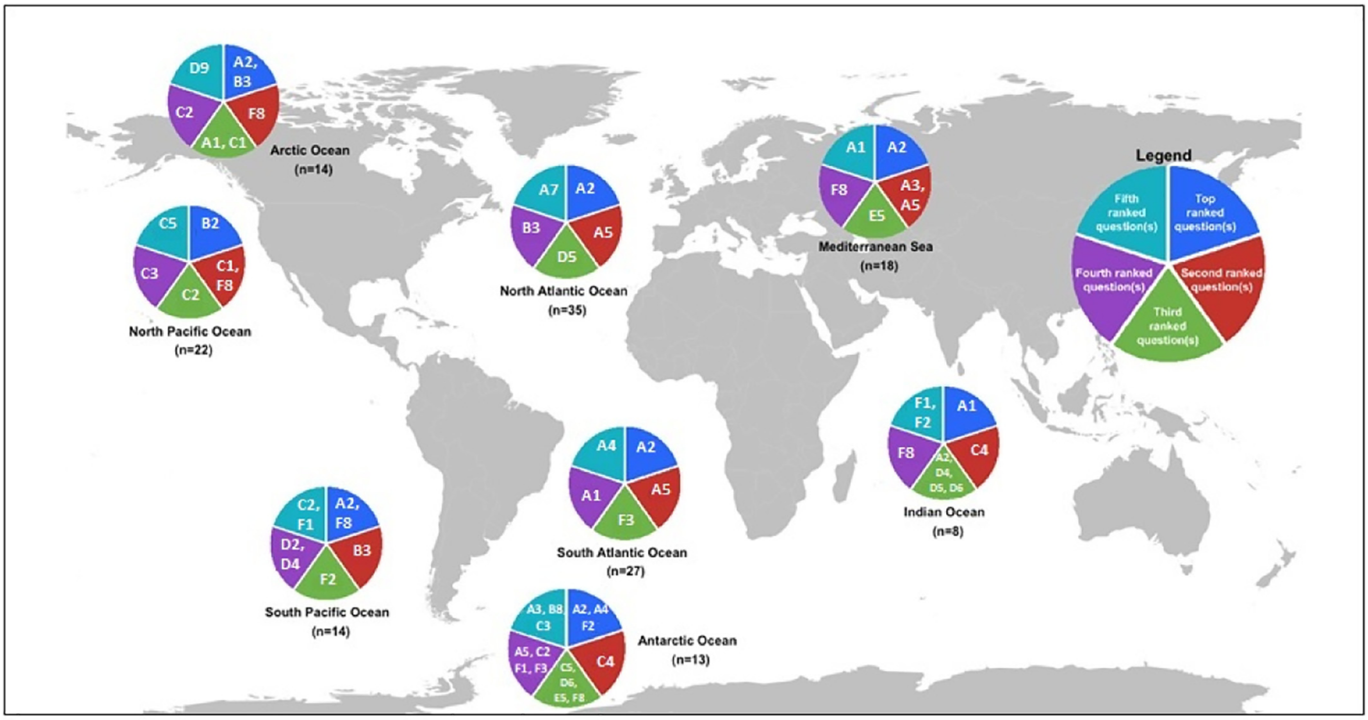

Fig. 5. Spatial distribution of the five top-ranked research questions as ranked by survey respondents ($n = 151$, including researchers who work in multiple regions) by marine plastic pollution research region. In each pie chart the alpha-numeric code refers to the questions that were the top 5 ranked questions in each region. The letters represent the following themes: A - *Sources, circulation, and distribution of plastics*, B - *Characterization of risk and vulnerability to plastic*, C - *Types of harm from plastics*, D - *Scale of harm of plastics on biota*, E - *Detection of ingested plastics and the associated problems*, and F - *Related economics and policy to ingested plastics.* Each letter indicates a different question under these themes (see Table 1).

sources and thereby have the leverage to stop emissions of plastic waste in the environment (GAIA, 2019; Li et al., 2016).

Questions in Theme A (*Sources, circulation and distribution of plastics*) were highly ranked by most expert groups, was represented by at least one question in the five top-ranked questions for all the regions except the North Pacific, and was the main theme identified by respondents in developing, in-transition and unranked nations. Reducing the impacts of plastic on biota requires a clearer understanding of where plastic pollution is coming from, and who is responsible for it. Understanding the spatial patterns of emissions of plastic into the environment requires the availability of local waste management data (i.e., community-level waste generation and recovery rates, waste management processes, and litter rates) as well as plastic production data. Such data needs to be reported in a systematic way and openly available for governments and researchers to use (Kaza et al., 2018). Policymakers and researchers need to work together to align data collection and data needs at multiple levels of governance. New research is shedding light on the oceanographic dynamics that influence the behaviour of plastics in the environment (Lebreton and Andrady, 2019); however, more work is needed to fully understand the distribution and fate of plastic pollution in the environment.

Another highly ranked research question was related to policy tools, F8 - "*What policy tools have been successful at reducing ingested plastics in aquatic biota*?", which was ranked high across nations, regions, and overall. There are few policy tools that have been implemented and for which wildlife have been used to monitor explicitly, but one example is the Convention for the Protection of the Marine Environment of the North-East Atlantic, or OSPAR Convention, which uses Northern Fulmars (*Fulmarus glacialis*) to track plastic pollution and is an example of a link between policy and reduction of impacts on biota (van Franeker and Law, 2015). Yet, while the Northern Fulmar is a useful indicator species for policy in the North Sea, it only inhabits the northern sections of the North Pacific and North Atlantic oceans, so it is of limited use elsewhere (Provencher et al., 2017). Other time-series, however, may be used to measure the impact from legislation or policy at the local or regional scale (e.g. Henderson, 2001). Despite a suite of policies and actions aimed at reducing plastic emissions to the environment, the volume of plastic in aquatic ecosystems is predicted to increase considerably due to demand and production increases (Borrelle et al., 2017) so the development of metrics to assess the effectiveness and impact of legislation, policies, and actions across the globe is clearly urgent.

The third-highest ranked question by all respondents was C2 – "*What are the chemical effects to aquatic biota from ingesting plastics*?". This was also echoed in the additional questions added by respondents (Table A, SOM). There is a growing body of literature exploring how contaminants, both plastics additives and other environmental contaminants that sorb to plastic pollution, can affect biota via ingestion. There are equivocal findings with studies demonstrating that some contaminants are associated with plastics ingestion (e.g. Chua et al., 2014; Tanaka et al., 2019), while others finding that plastic ingestion is not associated with higher concentrations (e.g. Provencher et al., 2018). Given the known links between plastic ingestion and chemical contaminants, particularly in species destined for human consumption, there is still a need to understand the transfer of contaminants via plastic pollution, and partitioning this from other contaminant sources, such as prey or atmospheric transport. This also becomes important as emerging chemicals are identified in plastic pollution, and their presence is detected in biota (e.g. Lu et al., 2018).

Across all survey respondents, those in developed, and in developing, in-transition and unranked nations consistently placed question E5 - "*What are the best methods for implementing standardized approaches for sampling and reporting of ingested plastics*?" in the five top-ranked questions. This call for standardized approaches is a common theme throughout English-language publications (e.g. Hidalgo-Ruz et al., 2012). While the number of publications examining ingested plastics across taxa has increased over recent years (Provencher et al., 2017), there are few standardized protocols for plastic studies in biota. Arguably, plastic ingestion methods have some of the most standardized approaches available in the plastic pollution research community, with protocols in the peer-reviewed literature for seabirds (Provencher et al., 2019), and recommendations for sampling methods for fish and invertebrates (Lusher et al., 2017). The results of this survey indicate that these methods are a priority, echoed in plastic research areas beyond biota, such as recent research and policy discussions (Goverment of Canada, 2019).

The research question A1 - "*Where are the areas of highest concentrations of plastics in the aquatic environment*?" was also ranked highly by all respondents across nation development status and geographic regions, and was ranked fifth overall. Though plastic studies are increasing, this finding suggests agreement that we still lack a robust understanding of which regions and zones within the environment have the greatest plastic concentrations and therefore, where biota are most likely exposed to plastic pollution and its potential detrimental effects (e.g. Young et al., 2009). This priority aligns with how plastic pollution does not affect all regions and species equally, and global overviews may not provide the resolution needed for identifying and intervening in regional plastic pollution problems. Existing literature discusses the importance of determining what species or populations may be most vulnerable to plastics to understand how conservation of vulnerable species could be carried out (Avery-Gomm et al., 2018).

Collectively, the five highest-ranked questions by respondents covered several aspects of plastic contamination in the environment: first, the source and fate of plastic pollution to the environment (A2), including the location of the areas of highest concentrations (A1). The effects associated with ingested plastic pollution in biota (C2) are also represented. Methods for quantification are also included (E5), as are policy tools to reduce plastics in the environment (F8). Research areas across the pollution cycle should be prioritized in funding calls and research policy development, along with those that address multiple priorities and knowledge sharing. This includes transparent and open access waste management, and plastic pollution data and 'grey' information so that other streams of research can access existing knowledge to address similar but different aspects of plastic pollution research.

4.2. Emerging priorities

While there is some overlap in highly-ranked research questions between our results and those discussed in a similar Horizon Scan on effects of plastics on wildlife by Vegter et al. (2014) there are a few notable differences between the list of priorities, perhaps due in part to the rapid expansion of the field of plastic pollution over the last few years. Vegter et al. (2014) elicited opinions from authors that had published papers from 2007 to 2012, while we included authors of papers to the end of 2016. Between 2012 and 2016, several notable changes in the field of plastic pollution research occurred, including one of the first empirically-based models of global plastic pollution (Eriksen et al., 2014), the quantification of plastics in everyday consumer foods such as table salt (Kim et al., 2018; Yang et al., 2015), beer (Liebezeit and Liebezeit, 2014), and fish destined for human consumption (Choy and Drazen, 2013; Liboiron et al., 2016; Rochman et al., 2015; Van Cauwenberghe and Janssen, 2014), as well as in Arctic and Antarctic environments (Lusher et al., 2015; Obbard et al., 2014; Trevail et al., 2014). Terms of art such as nanoplastics (Besseling et al., 2014; da Costa et al., 2016), plastisphere (Zettler et al., 2013) and plastiglomerate (Corcoran et al., 2014) also arose during this time. These advances point to how the field of plastic pollution has changed radically in the short time between surveys, and how both expert and popular discourses have changed with it.

Given such changes, it makes sense that several of the research priorities identified here (e.g., the negative impacts on plastics in fisheries and seafood) were not discussed by experts solicited by Vegter et al. (2014). These contrasts are also the result of differences in study design; plastics in relation to fisheries and human health were not listed by the experts in Vegter et al. (2014) likely because fish and invertebrates were not the focus of the literature reviewed, and therefore the taxonomic experts involved in the paper. While fish ingestion of plastics and entanglement received relatively less attention in the 20th century, the literature on plastics interactions in this group has since grown rapidly (Lusher et al., 2017; Provencher et al., 2017). There are now several papers that report on plastic ingestion in fish and invertebrate species that are regularly consumed by humans (Choy and Drazen, 2013; Davidson and Dudas, 2016; Liboiron et al., 2019; Rochman et al., 2015).

A significant difference between the two surveys is the perception of how well the impacts and effects of ingested plastics are established (Vegter et al., 2014), with more recent reviews (Rochman et al., 2016) and our survey identifying a better understanding the impacts of plastics as a priority. While there are many reports of effects at the individual level, evidence of population-level impacts is still largely lacking (Rochman et al., 2016). Indeed, in many jurisdictions, even baseline information in well-studied groups like seabirds, including which species are affected, where, and how severely is entirely absent or out of date (O'Hanlon et al., 2017; Provencher et al., 2015).

It is important to note that the priorities identified were mostly biophysical in nature, and not social. This is likely a function of those authors that have published on plastic pollution in biota to date. As the field expands and more researchers study plastic pollution from a variety of perspectives, there will be new perspectives and additional priorities in the coming years.

5. Conclusions

The recognition that plastic pollution is an important and intensifying environmental contaminant has grown in recent years. This has led to a dramatic increase in research on plastic pollution in the environment and its impact on biota, ecosystems, and human health. In response to an increased understanding of the pervasiveness of plastics in the environment, the associated negative effects, and in public awareness of the issue, governments (local, regional, and national) have made plastic pollution research a priority for funding and research. This is a welcomed move by the research community. The highly-ranked policy-relevant research questions from our survey will allow the research community to best contribute to actions and inform policies that will help reduce plastic pollution and its impacts on the environment.

CRediT authorship contribution statement

J.F. Provencher: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Project administration, Resources, Software, Supervision, Validation, Visualization, Writing - original draft, Writing - review & editing. **M. Liboiron:** Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Project administration, Software, Supervision, Validation, Visualization, Writing - original draft, Writing - review & editing. **S.B. Borrelle:** Conceptualization, Formal analysis, Investigation, Methodology, Validation, Visualization, Writing - original draft, Writing - review & editing. **A.L. Bond:** Conceptualization, Formal analysis, Investigation, Methodology, Validation, Visualization, Writing - original draft, Writing - review & editing. **C. Rochman:** Conceptualization, Formal analysis, Investigation, Methodology, Validation, Visualization, Writing - review & editing. **J.L. Lavers:** Conceptualization, Formal analysis, Investigation, Methodology, Validation, Visualization, Writing - review & editing. **S. Avery-Gomm:** Conceptualization, Formal analysis, Investigation, Methodology, Validation, Visualization, Writing - review & editing. **R. Yamashita:** Conceptualization, Formal analysis, Investigation, Methodology, Validation, Visualization, Writing - review & editing. **P.G. Ryan:** Conceptualization, Formal analysis, Investigation, Methodology, Validation, Visualization, Writing - review & editing. **A.L. Lusher:** Conceptualization, Formal analysis, Investigation, Methodology, Validation, Visualization, Writing - review & editing. **S. Hammer:** Conceptualization, Formal analysis, Investigation, Methodology, Validation, Visualization, Writing - review & editing. **H. Bradshaw:** Conceptualization, Formal analysis, Investigation, Methodology, Validation, Visualization, Writing - review & editing. **J. Khan:** Formal analysis, Investigation, Validation, Visualization, Writing - review & editing. **M.L. Mallory:** Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Resources, Validation, Visualization, Writing - original draft, Writing - review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

We are appreciative of all the experts who took the time to complete our survey. Without these community efforts and contributions, this study would not be possible. JFP was funded by the G. W. Garfield Fellowship for Northern Studies, administered via the Association of Canadian University for Northern Studies. ML was funded by the Northern Contaminants Program (NCP), the Social Science and Humanities Research Council (SSHRC), The Marine Environmental Observation Prediction and Response Network (MEOPAR) and Memorial University. SBB was funded by the David H. Smith Postdoctoral Conservation Research Fellowship. ALB was supported by the Natural History Museum, JLL and ALB were both funded by the Detached Cultural Organization. HB was funded by The Marine Environmental Observation Prediction and Response Network (MEOPAR). MM was funded by the National Science and Engineering Research Council of Canada (NSERC). Many thanks to Isabeau Pratte who assisted with the graphics. Comments from three anonymous reviewers improved this manuscript.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scitotenv.2020.139381.

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