Spatial–Temporal Growth, Distribution, and Diffusion of Marine Microplastic Research and National Plastic Policies

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Abstract Plastics account for 80% of material waste in the ocean. The field of marine microplastic (MP) research is relatively new and growing rapidly, in terms of published papers as well as institutions and countries conducting research. To combat plastic pollution, there is sufficient evidence that policies can lead to reduced plastic production and consumption both locally and globally. We aim to understand how marine MP research and national plastic policies have individually grown and spread. Specifically, we used scientometric and spatial diffusion methods to best explain how ideas (science and policy) clustered and spread geographically through time. We performed systematic literature searches to determine the spatial and temporal growth of marine MP publications and national plastic policies from 1900–2019. We found that more countries adopted national plastic policies than those that have conducted marine MP research. At each level of analysis (publication, institution, and country levels) within each field (research and policy), the temporal growth rate had a break point where doubling time changed significantly. Marine MP research grew exponentially, where doubling times ranged 1.1–3.7 years and the topics of inquiry increased steadily. National plastic policies also grew exponentially, where doubling times ranged 3.3–4.1 years. Different diffusion methods explain spatial growth, where marine MP research spread was best explained by a hybrid of expansion and relocation diffusion while national plastic policy spread was best explained by expansion diffusion. Both marine MP research and national plastic policies continue to spread, increasing global knowledge and mitigation efforts of plastic pollution.

Keywords Scientometric · Scopus · Hot spot · Pollution · Debris

1 Introduction

Global plastic production has grown since the late 1940s and today over 300 million tons of plastic is produced globally each year with no slowing in sight (Jambeck et al., 2015; Plastics Europe, 2018). As of 2015, over 6300 megatons of plastic waste was produced and only ~9% was recycled (Geyer et al., 2017). The majority of the plastic is from single use
packaging, construction, and textile/apparel (Geyer et al., 2017). Unfortunately, elements that contribute to plastic’s popularity, such as flexibility, durability, light weight, and low price, also contribute to the long-lasting environmental impacts. For example, plastic does not readily degrade, but instead breaks into smaller and smaller pieces termed “microplastics” (MPs; 1µm–5 mm; Arthur et al., 2009 Hartmann et al. 2019).

In the ocean, material waste in surface, pelagic, benthic, and beach environments is up to 80% plastic (Barnes et al., 2009; Choy et al., 2019). In addition to its overwhelming abundance, plastic acts as a sponge and a transportation vector for persistent organic pollutants (POPs) like DDT and PCB (Rios et al., 2007; Engler, 2012; Avio et al., 2015; Jambeck et al., 2015) and pathogens (Bowley et al., 2020). Plastic exposure has been shown to affect marine organisms mechanically due to the physical structure (Browne et al., 2008) and chemically due to the reactivity of attached toxics (Paul-Pont et al., 2016).

The field of marine MP is relatively new, however, and as a result knowledge of potential biological implications is still growing (Barboza & Gimenez, 2015). Small plastics were first noted in marine animals in the late 1960s (albatrosses; Kenyon & Kridler, 1969) and in marine environments with biological implications in the 1970s (coastal waters; Carpenter & Smith, 1972). The term “microscopic plastic,” however, was not commonly used until 2004 (Thompson et al.) and was not shortened to “microplastic” until 2006 (Ng & Obbard, 2006). Since then, marine MP research has grown rapidly, in terms of published papers, institutions conducting research, and international collaborations (Barboza & Gimenez, 2015). This increase is mainly driven by an increase in laboratory microcosm experiments studying the effects of MP in a controlled environment (Barboza & Gimenez, 2015), but there has also been an increase in environmental (sediment and water) and organismal MP contamination studies (wild-caught; Ryan, 2015). Thus far, studies found organisms from multiple functional groups, including invertebrates, small vertebrates, large vertebrates, and zooplankton ingest plastic in laboratory experiments and in natural habitats (Thompson et al., 2004; Browne et al., 2008, Wright et al., 2013, Frias et al., 2014, Avio et al., 2015, Cole & Galloway, 2015; Desforges et al., 2015, Li et al., 2015, 2016; Harris & Carrington, 2019, Harris et al., 2021). Microplastics have the potential to accumulate in the food chain and detrimentally impact marine ecosystems through their physical presence as well as their ability to adsorb POPs (Rios et al., 2007; Galloway et al., 2017).

Recently, marine plastic pollution has become a hot topic in the press and among conservation organizations and non-government organizations (NGOs; e.g., the “Plastic or Planet” issue by National Geographic in June 2018; World Wildlife Fund ReSource: Plastic activation hub n.d.; Surfrider Foundation n.d.). Many of these groups demand a “call to action” for policies to be put into place to reduce both plastic production as well as pollution. Although the field of marine MP is relatively new, there is the overarching conclusion that MPs have negative organismal, social, and economic impacts (Beaumont et al., 2019).

To combat these negative effects, there is sufficient evidence that policies can lead to reduced plastic production and consumption both locally and globally (Ryan, 2015; Schnurr et al., 2018). At a local and regional level, conservation groups and NGOs are forming coalitions to lobby for anti-plastic bills and we are starting to see traction at the national level, where countries are starting to regulate the most common plastic items. Numerous sources of MPs make it difficult to regulate, so national policies tend to focus on consumer plastic like bags, microbeads, or single use plastic (SUPs), rather than production plastic (packaging and industrial material). By directing attention toward consumer plastics, countries can substantially decrease the quantity of low-grade plastic disposal and the subsequent pollution (Schnurr et al., 2018). Due to the structure of national governance and few international regulating systems, individual countries are left to implement their own versions of plastic policy that are dependent on national needs and demands as well as trade agreements with neighboring countries.

There is international recognition that marine debris is a pervasive pollution issue. Six international marine debris conferences (1984, 1989, 1994, 2000, 2011, 2018; Supplemental Table 1) have occurred and have developed a framework for reducing marine debris in addition to calling upon governments, NGOs, industries, and stakeholders to adopt it. The framework does not have any legal standing nor does it have incentives (other than environmental preservation) or implementation requirements. The European Union (EU) is one of the few international entities to
implement regulations with legal standing, as seen with their single-use plastic ban going into effect in 2021 (European Parliament News, 2019). Broader international regulating organizations (e.g., UN, NATO), however, have made slow (if any) progress implementing a unified approach to marine debris, and marine plastic pollution remains a pressing global issue today.

As the field of marine MP grows, national and international collaborations between marine MP scientists have increased (Barboza & Gimenez, 2015; Pauna et al., 2019). Notably the National Center for Ecological Analysis and Synthesis (NCEAS) working group (2011), Marine debris: Scale and impact of trash in ocean ecosystems, which brought together a global group of interdisciplinary scientists to address the global pollution issue. Furthermore, the quantity of organismal, environmental, and review publications have increased as well (Ryan, 2015). Widespread policy is often a result of more scientists conducting studies in more places and reaching out to their local governments (Powell & Bromley, 2012), emphasizing the importance of scientific research growth to achieve policy spread and growth. Although scientific research and public policy are often funded by different administrative bodies (e.g., agencies and legislature, respectively in the USA), increased collaborations and publications may be a proxy for a country’s motivation and resources regarding plastic pollution, resulting in the adoption of national plastic policies. It is important to note that regardless of scientific research as a proxy for motivation, other country-specific parameters such as cultures, NGOs, funding agencies, demands, and belief systems likely play important roles in policy adoption. It is probable that scientific research alone does not drive policy change, but rather that science informs country-specific parameters that increase motivation for national policies. Identifying if and how marine MP research and national plastic policies independently experience geographic spread may shed light on the factors driving each field’s rapid growth and may also establish a novel link between the two fields.

Given the hot topic of marine plastic and establishment of a marine debris framework, it is unsurprising that both marine MP research as well as national plastic policies are increasing globally (Barboza & Gimenez, 2015; Karasik et al., 2020). The spatial–temporal patterns explaining either marine MP research or national plastic policy growth and geographic diffusion remain unknown, however. Diffusion patterns arise from expansion or relocation properties that are often a result of external determinants such as motivation, obstacles against innovation, and resources for overcoming the obstacles (Berry & Berry, 1990; Mohr, 1969). Spatial analyses can therefore be used to determine how ideas (in this case science and policy) spread geographically through time, identify clusters, and lend evidence to distinguishing between diffusion properties.

Diffusion patterns and diffusive growth typically follow an S-shaped curve, showing the accumulation of adopters over time as entities (e.g., authors, institutions, countries) gain motivation and resources to overcome obstacles, from innovators to majority to laggards (Fig. 1A; Rogers, 1995). In fields that are still growing, like marine MP research or plastic policies, transitions between growth phases may be identified as break points in piece-wise regression analyses (Bormann & Mutz, 2015). If a diffusion is clustered, spatial analysis can reveal two types of spatial diffusion properties: (1) expansion and (2) relocation (Fig. 1B-C; Mitchell, 2018). Expansion occurs when ideas spread out geographically from one area and when adoption by nearest neighbors is more likely than adoption by non-neighbors. Relocation occurs when there are multiple geographical areas of adoption which can be identified through clustering of dispersed adopters. Hybrid diffusion occurs when both expansion and relocation diffusion are observed at the same time.

Examining diffusion as a function of time and space can offer insight to how these fields are growing, if and how spread is occurring, and may point toward why they are spreading (Mitchell, 2018; Shipan & Volden, 2008). Growth and diffusion affect geographical patterns, which can be analyzed for spatial relationships over time with hot spot analyses. Hot spot analyses are common in crime, accident, and epidemiology research (e.g., Moore & Carpenter, 1999; Anderson, 2009; Erdogan et al., 2008) and can be useful to visualize event centers over time. If ideas are expanding geographically and institutions or countries are clustered, hot spots will remain in the same locations over time. If ideas are relocating across geographic space, hot spots will shift and jump locations
over time. Diffusion is considered hybrid if multiple diffusion properties are evident in visualization.

This paper investigates the spatial–temporal growth, distribution, and diffusion of plastic research and national plastic policies. Due to the vast field of marine plastic research, we used marine MP papers as a manageable case study. We use scientometric and spatial diffusion methods to determine how ideas (in this case science and policy) grow spatially and temporally. We propose six independent hypotheses and associated justifications:

**H1 Global marine MP publications are growing exponentially at the paper, institution, and national levels**

Marine MP publications as well as collaborations are growing quickly (Barboza & Gimenez, 2015; Ryan, 2015). As more researchers study and publish marine MPs papers, institutions and countries will increase with similar growth trajectories.

**H2 Marine MP papers are increasing in breadth of topics studied**

The quantity of topics and organisms studied will increase as new researchers, collaborators, and institutions increase (Barboza & Gimenez, 2015) and start building new marine MP programs.

**H3 Countries implementing national plastic policies are growing exponentially**

Increased attention toward marine plastic pollution and relatively recent international commitments to reducing plastic waste (e.g., EU plastic ban) will increase the quantity of countries implementing national plastic policies.

**H4 Countries publishing more marine MP papers are more likely to have national plastic policies than countries publishing fewer or no papers.**

Marine MP research is a proxy for a country’s motivation and resources regarding plastic pollution; therefore, countries with more papers published will have high amounts of motivation and resources to adopt national plastic policies.
Institutional marine MP research growth is in the early majority phase and spread is due to relocation diffusion

As a new field with momentum, marine MP research is still in the beginning phase of its growth trajectory. With the rise of marine MP publications and international collaborations (Barboza & Gimenez, 2015), the field will spread to non-neighboring countries creating a relocation diffusion pattern.

National plastic policy growth is in the early majority phase and spread is due to expansion diffusion

Neighboring countries are often culturally similar, and while countries are left to implement their own plastic policies, they are likely to be influenced by neighboring countries with similar cultures, creating growth and expansive diffusion. Countries are implementing their own plastic policies, and will continue until the majority of countries have done so, reaching a saturated state.

2 Methods

2.1 Marine Plastic Peer Reviewed Paper Selection

Growth of marine microplastic (MP) publications was compared to other types of plastic research by performing a systematic literature search of peer-reviewed papers from Scopus, Elsevier’s abstract and citation database, in April 2020. The search used five sets of keywords: marine AND plastic*, marine AND “plastic bag*,” marine AND “single use plastic*,” marine AND microbead*, and marine AND microplastic*. The asterisk at the end of a word ensured both the singular and plural forms were considered. The first set of keywords, marine AND plastic*, was chosen to represent the broader field. Sets of keywords including “plastic bag*,” “single use plastic*,” and microbead, mirror the national plastic policy foci selected in this study. The set of keywords, marine AND microplastic*, was selected to equate the Scopus searches to the Web of Science search, outlined below. Within each of these sets of keywords, the “analyze search results” feature was used in Scopus to record the quantity of papers published annually and cumulative number of papers published by country for 1900–2019. We note that many early papers studying mussel feeding physiology used poly-microbeads since the 1980s but were not included in any of the keyword searches (e.g., Ward, 1996). Papers were randomly spot-checked to ensure they fit within the keywords.

Metadata from marine MP papers were collected from a systematic literature search of peer-reviewed papers from Web of Science in April 2020. The search criteria used were the keywords marine AND microplastic* and all years (1900–2019), the same as the Scopus search. Publishing date, institution of lead author (including latitude and longitude), country of lead author, journal, and title were collected. Papers addressing non-marine MP topics (e.g., table salt or freshwater), highlights, commentary, news features, correspondences, opinion, and review papers were removed.

Each marine MP paper was categorized based on focus topic: chemistry, environment, organism, policy, or review. If a paper studied multiple focus topics, only the predominate one was recorded. Organismal papers were further categorized into functional groups: bacteria, fungus, invertebrate, small vertebrate, large vertebrate, macroalga, phytoplankton, and zooplankton (includes fish larvae). If a paper studied multiple organisms, all organisms were categorized by functional group and included.

2.2 National Plastic Policy Selection

To evaluate plastic policy growth and diffusion, a systematic literature search for national plastic policies implemented through 2019 was conducted. The plastic policy literature search included three predominant types of plastic, plastic bag, microbead, and single use plastic (SUP), at two levels, levy and ban. Policy data was collected from Xanthos and Walker (2017), Schnurr et al. (2018), Lam et al. (2018), Plastic Policy Inventory from Duke’s Nicholas Institute for Environmental Policy Solutions (2020), and news articles from Wikipedia’s “phase-out of lightweight plastic bags” page (2020). Country, implementation year, type (plastic bag, microbead, SUP), and level (levy, ban) were recorded. All policies were cross-validated with an internet news search and policies that failed cross-validation were not included. Voluntary national plastic levies and bans were not included. Policies were evaluated at a national level, where
countries with multiple levels or types of policies were only counted once in analyses. Local policies (city, county, state, etc.) were not included in these analyses as globally there is relatively poor documentation at such a fine scale.

2.3 Analysis

All analyses, maps, and graphs were developed with the computing software R for Mac OS X (version 3.6.1, R Core Team, 2019). The following packages were used: lme4, plyr, ggplot2, rworldmap, maptools, segmented, and spatstat. For all tests, level of significance was set at $\alpha < 0.05$.

Semi-ln regression was used to analyze temporal growth rate and doubling time of plastic research papers appearing in Scopus. ANCOVA was used to assess marine MP research from Scopus and Web of Science with source as the main effect and year as the covariate. Chi-squared was used to analyze the observed distribution of focus categories in marine MP papers as compared to the predicted distributions.

Change in growth rates of marine MP papers, institutions publishing, countries publishing, and countries with national policies were tested for using Davies’ test. If a change was indicated, piecewise semi-ln regression analyses were used to estimate the years where the break points occurred. Linear models were used to characterize the temporal growth rate and doubling time of each segment. A $t$ test was used to compare the quantity of marine MP papers published in countries with and without plastic policies.

2.4 Diffusion

Two diffusion properties were compared in both marine MP papers and plastic policies, expansion and relocation. Kernel density estimations for each year (where there were enough papers or policies to do so) were calculated to explore which type of diffusion best explained the spread and clustering of papers and policies over time. Kernel density estimations were plotted each year for latitude and longitude of papers and policies. Papers were evaluated at the institution level and policies at the national level. Hot spot analyses were used to visualize geographic concentrations (Anderson, 2009) of institutional marine MP publications over time (spread). Institution coordinates and country centroid coordinates (latitude and longitude) were used for analyses and institution coordinates and country polygons were used for visualizations. All national policies types were assessed together (plastic bags, microbeads, and SUPs).

3 Results

3.1 Scopus

Marine plastic literature dates back to 1961, when the first study using plastic in marine industries was published (Strickland & Terhune, 1961). However, the first report of marine plastic pollution was not published until 8 years later (Kenyon & Kridler, 1969). The field of marine plastic (whether related to industry or pollution) has grown exponentially, doubling on average every 7.7 years, similar to climate change publications and faster than scientific publications as a whole (Table 1). Our search of marine AND plastic* literature yielded a total of 7577 papers (after random spot-checking); we therefore consider the dataset to serve as a good representation of the broader field (Fig. 2).

Marine AND “plastic bag*” literature dates back to 1961 where a study used plastic bags as a research tool (Strickland & Terhune, 1961). For 30 years, plastic bags were used as pollution confinement measures (oil) or for in situ experiments. The first marine plastic bag record relating to pollution available in Scopus was a study on manatees (Beck & Barros, 1991). Marine AND microbead* literature dates to 2004 and the use of fluorescent poly-microbeads in current and water flow studies (Petrisor et al., 2004), however it was not until 2013 that marine microbeads were recognized as pollution in research. The field of marine AND “single use plastic*” is the newest, with the first papers published in 2017 (Wagner, 2017; Xanthos & Walker, 2017). Both of the studies published in 2017 address the efficacy of single use plastic bans rather than any marine aspect. All of the aforementioned fields have grown exponentially with varying doubling times ranging from 1.2 to 8.7 years; the SUPs literature was too recent to include in this doubling rate analysis (Fig. 2; Table 1).
3.2 Marine Microplastic Papers

We used marine microplastic (MP) papers as a manageable case study for investigating spatial–temporal patterns and diffusion properties. Marine MP papers were published more than any other keyword within marine plastic \(p<0.001; \chi^2\), exceeding plastic bag, microbead, and SUP publications by 8, 11, and 86 times, respectively (Fig. 2). There was no significant difference between the quantity of marine MP papers collected over time from Scopus and Web of Science \(p=0.98\); ANCOVA; Supplemental Table 2; Supplemental Fig. 1).

As of the end of 2019, 538 institutions in 64 countries (of 195 countries, not all of which have marine territory) published a total of 1267 marine MP papers (Table 2). Each level of analysis (paper, institution, and country) had a break point where growth rate changed significantly \(p<0.01\); piecewise semi-In regression; Fig. 3, Table 1). Marine MP publication rate slowed in 2014 from a doubling time of 1.1 to 1.5 years, institutional publication rate slowed in 2012 from a doubling time of 1.3 to 1.7 years, and country publication rate slowed in 2009 from a doubling time of 3.4 to 3.7 years. We label the institutions and countries from the first publication to the break point as early adopters and from the break point till 2019 as early majority; we acknowledge that we cannot separate innovators and early adopters precisely because marine MP research is still growing exponentially (Fig. 3).

| Table 1 | Summary of doubling time (years) analyses. (A) Other scientific fields, (B) Scopus keyword search, (C) marine microplastic papers at the paper, institution, and country level divided into early adopters and early majority, and (D) plastic policies at the country level divided into early adopters and early majority. Data on doubling times for other scientific fields were collected from the following sources: Science from Bornmann & Mutz, 2015 and climate change from Haunschild et al., 2016 |
|-----------------|-----------------|-----------------|-----------------|
|                 | Years           | Doubling time   |                |
|                 |                 | (years)         |                |
| A) Field        |                 |                 |                |
| Science         | 1980–2012       | 24              |                |
| Climate Change  | 1980–2014       | 5–6             |                |
| B) Scopus keyword search: Marine AND plastic* | 1961–2019 | 7.7 |
| "plastic bag**" plastic* | 1961–2019 | 8.7 |
| microbead*      | 2004–2019       | 3.1             |                |
| microplastic*   | 2006–2019       | 1.2             |                |
| "single use plastic***" plastic* | 2017–2019 | NA |
| C) Marine microplastic papers | | |
| Papers          | 2006–2014       | 1.1             |                |
|                 | 2015–2019       | 1.5             |                |
| Institutions    | 2006–2012       | 1.3             |                |
|                 | 2013–2019       | 1.7             |                |
| Countries       | 2006–2011       | 3.4             |                |
|                 | 2012–2019       | 3.7             |                |
| D) Plastic policies | | |
| Countries       | 1993–2009       | 4.1             |                |
|                 | 2010–2019       | 3.3             |                |

3.3 Policies

By the end of 2019, a total of 127 national plastic policies were implemented in 115 countries, placing either a ban and/or levy on plastic bags, microbeads, and/or single use plastics (SUPs; Table 4; Supplemental Table 3). Notably, the number of plastic bag policies has tripled globally in the past 10 years (2010–2019). Some countries progressed from a levy to a ban of the same type of plastic, some countries have multiple policies regulating different types of plastics, and some have just one type of plastic policy. Here, we examined plastic policies from a national level, where countries with multiple types or levels of policies were only counted once. The growth trajectory of countries adopting national plastic policies exhibited a break point, where adoption rate changed in 2010 from a doubling time of 4.1 to 3.3 years (piecewise semi-In regression; Fig. 3; Table 1). As with marine MP papers, adoptions of national policies are still growing exponentially; we labeled countries from the first adopter to the break point as early adopters and from the break point through 2019 as early majority.
Denmark was the first country to adopt a national policy (plastic bag levy) in 1993, and Bangladesh was the first country to successfully adopt a national ban (plastic bag) in 2002. Saint Lucia was the first country to adopt a national SUP levy in 2008 and Guyana was the first country to adopt a national SUP ban in 2014. As of 2019, SUP policies only exist in the Caribbean and South America. The USA was the first country to adopt a national plastic microbead ban in 2015. Plastic bag legislation is the most common type of national plastic policy, with only a few countries enforcing microbeads and SUPs policies (Table 4; Supplemental Table 3).

More countries adopted national plastic policies than those conducting marine MP research, and the growth rate differs between the two metrics (115 and 64, respectively; \( p < 0.01 \); Davies’ test; Fig. 3). Further, there is no difference in quantity of marine MP papers published by countries with or without national plastic policies (all types of policies combined; \( p = 0.12 \); \( t \) test; Supplemental Fig. 2).

### 3.4 Diffusion

Institutions publishing marine MP papers have historically been, and continue to be, concentrated in the Northern hemisphere (Fig. 5). While Europe continues to be a dominant hot spot for MP research, institutions conducting research spread longitudinally over time, flattening the kernel density estimation curve (Fig. 5). From 2013 to 2019, the quantity of hot spots condenses from four to two, signifying dominant leaders in the marine MP field. These two hot spots are Europe, which continuously maintains high kernel density estimations, and Eastern China, which emerges in 2016 with lower kernel density estimations (Fig. 5). These estimations and visualizations suggest hybrid diffusion is present, with expansion of the Europe and Eastern China hot spots as well as relocation observed in the decrease of hot spots.

Conversely, countries with national plastic policies (all plastic policies evaluated together) have historically been, and continue to be, evenly spread across both Northern and Southern hemispheres (Fig. 6). Kernel density estimates for national plastic policies are highest near zero degrees longitude (Fig. 6C). Plastic policies were evaluated at the national level and therefore hot spot analyses were not visualized. While more spatially dispersed in 2011, national plastic policies are concentrated across African and European countries as of 2019. When examining kernel density estimations and geographic visualizations,
expansive diffusion, where hot spots remain in the same regions, was predominantly observed.

4 Discussion

Marine plastic pollution has been documented in scientific literature since the late 1960s and continues to be a growing research topic and policy concern. We used aspects of scientometric and spatial diffusion research to understand the spatio-temporal growth of marine microplastic (MP) research and national plastic policies. This study shows evidence to support our hypotheses that marine MP publications are increasing exponentially at all levels (H1) as well as increasing in breadth of topics studied (H2), national plastic policies are increasing exponentially (H3), and national plastic policy spread is due to expansion diffusion (H6). This study did not find evidence that countries with more published marine MP research had national plastic policies
(H4) nor that marine MP research spread is solely due to relocation diffusion (H5). The results point to a heterogeneous, hybrid spread of global research activity and policy implementation with different diffusion properties.

Marine MP papers were used as a manageable case study for the broader marine plastic field. We note that research on marine MPs existed before the keyword was termed and is encompassed by marine plastics research in general. The term “microplastic” (rather than microscopic plastic or small plastic) is relatively new (2006) and previous research on MPs may have been omitted from our search. We are confident, however, that the collection of marine MP papers we did identify serves as a good case study for growth and diffusion patterns.

Marine MP research has grown exponentially at the publication, institution, and national levels, doubling every 1.1–1.5 years since 2006, faster than scientific publications as a whole (Table 1). Published marine MP papers focus on a breadth of topics, the most popular being organismal and then environmental. Together, organismal and environmental studies account for over half of the published papers (Fig. 4) and likely drove the exponential rate of marine MP publication through the rise of microcosm studies (organismal; Barboza & Gimenez, 2015) as well as regional monitoring.

Fig. 3 (A) Cumulative and (B) semi-ln cumulative marine microplastic papers; (C) cumulative and (D) semi-ln cumulative institutions publishing marine microplastic papers; and (E) cumulative and (F) semi-ln cumulative countries publishing marine microplastic papers and countries with national plastic policies. Papers retrieved from Web of Science for the keywords marine AND microplastic* with publication dates of 2006–2019. Piecewise regression break points, where slope of line significantly changes, is present in all semi-ln cumulative graphs. One asterisks (*) represents statistical significance of slope change at \( p < 0.01 \) and two asterisks (**) represents statistical significance of slope change at \( p < 0.001 \); Davies’ test. Gray shading represents 95% confidence intervals for each line fit.
efforts (environmental; Ryan, 2015). Furthermore, over 32% of organismal papers focused on multiple rather than a single species, emphasizing the interest in trophic transfer, food webs, and ecosystem-level approaches in the marine MP problem. The most common functional groups studied within organismal papers were small vertebrates (e.g., fish) and invertebrates (e.g., oysters, mussels, crabs), both important in aquaculture and human consumption, relatively easy to perform mesocosm experiments on or capture in the wild, and perhaps carry higher economic research incentives.

Marine MP research is still in the early phase, including innovators, early adopters, and early majority, as identified by the initial phase of the typical S-curve (Fig. 1A: Rogers, 1995). As of the end of 2019, there appears to be no slowing of publication rate. Perhaps, this trend is in part due to early adopting researchers and institutions (e.g., within the UK and the USA) building and expanding individual programs, becoming experts, forming both domestic as well as international collaborations (e.g., Thompson et al., 2004; Barboza & Gimenez, 2015; Pauna et al., 2019), and thus promoting the establishment of an early majority. The concept of prolific, early adopting institutions is supported by kernel density

Table 3 Frequency of functional groups studied in marine microplastic papers from 2006–2019. Functional groups were determined from paper title, abstract, and results. Papers with multiple functional groups were counted multiple times

| Functional group | Frequency in published papers |
|------------------|------------------------------|
| Small vertebrate | 639                          |
| Invertebrate     | 357                          |
| Zooplankton      | 152                          |
| Large vertebrate | 59                           |
| Bacteria         | 53                           |
| Phytoplankton    | 16                           |
| Fungus           | 4                            |
| Macroalgae       | 4                            |

Table 4 Summary of national plastic policies reported as type as of 2019. A total of 127 national plastic policies were implemented in 115 countries

| Policy type | Year of first implementation | Quantity of national policies |
|-------------|------------------------------|------------------------------|
| Plastic bag | 1993                         | 113                          |
| Microbead   | 2015                         | 8                            |
| SUP         | 2008                         | 6                            |
estimates, where Europe starts as a hot spot in 2013, and remains one through 2019 (Fig. 5).

The development of scientific fields and disciplines is often driven by the pedigree of principle investigators and their students who subsequently move to other institutions and/or countries to continue their research. The field of marine MP is new and quickly growing, however, a marked decrease in growth rate occurred at each analysis level (paper, institution, and country). This indicates that while pedigree is important, many early career scientists from proficient research groups may have not had the time necessary to establish their own group and subsequently influence spatial diffusion patterns found here. We expect researchers trained during either the early adoption or early majority phases to substantially contribute to the field during the late majority phase. Further, MP research is collaborative, with researchers...
collaborating across disciplines, publishing “clusters” (authors that frequently publish with one another), and countries (Pauna et al., 2019). While the data-set includes influential and highly cited papers and individual authors that may have a larger impact on the research community and press, the new and collaborative nature of the field reinforces that quantity of published papers is an accurate metric to examine growth and diffusion.

At institutional and national levels of marine MP research analyses, the early majority phase is characterized by slower growth than the early adoption phase. Most diffusion literature suggests that later-adopting countries tend to adopt quicker, due to a decrease in perceived risk (e.g., Valente 1995; Albuquerue et al., 2007). We see the opposite trend here, where early adopting countries adopted quicker. This is possibly due to an observed opportunity to delve into a new, unexplored topic where everyone starts on equal footing and the initial perceived risk is low. Now, however, as the field of marine MP has grown, so has the breadth of topics and species studied, thus reducing novel study organisms that new programs and institutions may study. This is supported by the increase of studies focusing on multiple organisms rather than a single organism that has been saturated in previous studies. Furthermore, the advancement in best practices has called for expensive polymer analysis to validate results for publication (Granek et al., 2020).

**Fig. 6** Geographic visualization of national plastic policy types in (A) 2011 and in 2019. Both bans and levies are included and not differentiated in this geographic visualization. Color corresponds to the type of national plastic policy. Country centroids were used to analyze kernel density estimations of national plastic policies across (B) latitudes and (C) longitudes in 2011 and 2019.
These aspects of marine MP research present new obstacles to overcome for researchers or institutions trying to get into the field and may explain why we observed a decrease in publication rate after 2014. The research field remains undersaturated and many questions remain unanswered; however, researchers now face more barriers to entering the field if not already part of a research group then they did during the early adoption phase. The rate of publication at each level of analyses is likely going to increase during the late majority phase as early career researchers that were previously part of prolific marine MP research groups in the early adoption and majority phases (and thus have a lower barrier to entry) set up their own groups in different institutions and countries.

Marine MP research exhibited a hybrid of expansive and relocation diffusion. This could be for a multitude of reasons, and we suggest three explanations. First, scientific research is often collaborative, with the possibility of collaborators at multiple institutions between both neighboring and non-neighboring countries (Barboza & Gimenez, 2015; Ryan, 2015; Pauna et al., 2019). Second, globalization enables widespread communication and opportunities to learn about actions of non-neighboring countries, reducing the influential strength of neighbors. Third, research is mainly a product of wealthy countries with prestigious universities, concentrated in select regions. These three ideas, or their combination, could contribute to the hybrid diffusion pattern observed as well as lend insight to diffusion mechanisms at play.

The growth of countries researching marine MP is mirrored in the number of countries and researchers taking part in the past six Marine Debris Conferences (Supplemental Table 1) and international groups supporting pollution mitigation (e.g., EU and UN). Currently in the early majority phases, research and policies are being adopted by countries at similar rates (Table 1), though this was not always the case. Plastic policies were implemented at the national level since 1993, contributing the high number of countries with policies as opposed to research. It is important to note, however, that there is no limit to the number of papers that can be published while the total number of institutions and countries is relatively fixed. In the coming years, we may start to see growth rates of institutions and countries conducting research and adopting policy slow, as they approach saturation, while publication rates remain high.

Marine MP research, while potentially having economic incentive, is not a good proxy of the country’s interest or motivation for plastic policies. There appears to be no relationship between quantity of marine MP papers published by a country and presence or type of national plastic policy and we were unable to discern if marine MP research (or the larger body of plastic research) is directly contributing to the increase in plastic policies. To support these findings, countries with marine MP publications and countries with national plastic policies occupy different areas of the world (Figs. 5 and 6), where marine MP papers are concentrated in the Northern Hemisphere and have distinct hot spots, and national policies are spread between Northern and Southern hemispheres, in many developing countries.

We suggest that other country-specific parameters such as cultures, NGOs, funding agencies, demands, belief systems, and plastic industries likely play more important roles in policy adoption and should be further explored. Specifically, the influence of conservation-focused NGOs and the opposing plastic industry should not be overlooked. NGO involvement in environmental policy-making around the globe has increased substantially since the 1972 United Nations Conference on Human Environment (Betsill and Corell 2008), forming powerful coalitions that may influence both national as well as international plastic policies substantially. Conversely, the plastic industry, consisting largely of chemical and fossil-fuel companies, has continuously opposed plastic ban policies, opting instead for language that shifts away from producer responsibility to focus on recycling and consumer accountability. These two forces directly oppose one another and may overshadow any effect scientific research has on policy adoption.

The spatial distribution of national plastic policies may be due to difficulty associated with implementing nationwide policies and the historically ad hoc, bottom up trend observed with previous plastic bag policy studies (Clapp & Swanston, 2009). We also note that while clustering is present, it may have little to do with policy diffusion and more to do with political, economic, and demographic similarities often observed in geographically neighboring countries (Shipan & Volden, 2012). Clapp and Swanston (2009) explored the emergence of plastic
populated urban areas place higher demands and burdens on natural resources than rural communities, leading to a greater incentive to manage common-pool resources (e.g., fossil fuels), and issues like pollution (Ehrlich, 1968; Stern et al., 1992). Marine plastic pollution affects more than urban areas, however. Microplastics have been found in the Arctic Ocean and Antarctic Peninsula, both of which are places where there are no permanent industries (Cózar et al., 2017; Lacerda et al., 2019). Unfortunately, rural communities are still inundated by pollution from urban populations. Small islands in the Indo-Pacific have more plastic litter on beaches than they have people on the island—all due to ocean currents and global consumerism (National Geographic, 2018). While these countries and island nations have largely passed regulations banning types of plastics, it has not alleviated the issue.

The countries that are perceived as the most affected by marine plastic pollution are not a hot spot for marine MP research, while large urban centers such as Europe, China, and the USA are. This mismatch between where research is conducted, pollution is the worst, and policies are adopted may lead to underestimating how severe marine plastic pollution is and how much plastic policies can mitigate the issue. The science-policy mismatch may be accentuated in the future since marine MP publications displayed a marked decrease in growth at all levels of analysis (paper, institution, and country) while countries adopting policies displayed a marked increase in growth at the national level. This phenomenon may strengthen geographic publication hot spots in regions distinct from countries that need national plastic policies.

Assessing how scientific research contributes to and strengthens the durability and effectiveness of policies in countries that have both marine MP research as well as policy adoption can shed light on the intersection of the two fields. If science does strengthen policy then we expect to see compounding effects of the spatial mismatch between research, policy, and pollution hubs where countries that are the most polluted and need the most effective policies are not publishing the necessary scientific research that can strengthen implementation. Conversely, cultural and societal needs may lead to greater policy durability and effectiveness, and therefore diminishes the role science can play in policy-making and adopting. This study only recorded country of the first author rather than where the study was conducted, potentially further supporting both a discrepancy in research as well as factors other than marine MP publication influencing policy adoption.

Marine MPs are a local, regional, and global issue that require cross disciplinary attention from researchers in biological, chemical, environmental, and social sciences. We found that aspects of marine MP research explored here were not good indicators of a country’s resource or motivation toward national plastic policies and suggest exploring external (motivation, obstacles, and resources for overcoming the obstacles) and internal (e.g., GDP, culture, religion, plastic, and fossil fuel industries) factors to understand what is driving research and policy diffusion. Both marine MP research and national plastic policies continue to spread, increasing global knowledge and mitigation efforts of plastic pollution. As knowledge and mitigations efforts increase, there is a clear need for studies that explore external and internal factors driving research and policy diffusion as well as international science-based policies to reduce global marine plastic pollution.

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**Data Availability** The datasets generated during and/or analyzed during the current study will be available in the Dryad repository upon acceptance.

**Code Availability** The code generated during the current study is available from the corresponding author on reasonable request.

**Declarations**

**Ethics Approval** Not applicable.

**Consent to Participate** Not applicable.

**Consent to Publication** Not applicable.

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**References**

Albuquerque, P., Bronnenberg, B. J., & Corbett, C. J. (2007). A spatiotemporal analysis of the global diffusion of ISO 9000 and ISO 14000 certification. *Management Science, 53*(3), 451–468. https://doi.org/10.1287/mnsc.1060.0633.

Anderson, T. K. (2009). Kernel density estimation and K-means clustering to profile road accident hotspots. *Accident Analysis & Prevention, 41*(3), 359–364. https://doi.org/10.1016/j.aap.2008.12.014.

Arthur, C., Baker, J., & Bamford, H. (2009). National oceanic and atmospheric proceedings of the international research workshop on the occurrence, effects, and fate of microplastic marine debris. Proceedings of the International Research Workshop on the Occurrence, Effects and Fate of Microplastic Marine Debris, NOAA Technical Memorandum NOS-OR&R-30.

Avio, C. G., Gorbi, S., Milan, M., Benedetti, M., Fattorini, D., d’Errico, G., Pauletto, M., Bargelloni, L., & Regoli, F. (2015). Pollutants bioavailability and toxicological risk from microplastics to marine mussels. *Environmental Pollution, 198*, 211–222. https://doi.org/10.1016/j.envpol.2014.12.021.

Barboza, L. G. A., & Gimenez, B. C. G. (2015). Microplastics in the marine environment: Current trends and future perspectives. *Marine Pollution Bulletin, 97*(1), 5–12. https://doi.org/10.1016/j.marpolbul.2015.06.008.

Barnes, D. K. A., Galgani, F., Thompson, R. C., & Barlaz, M. (2009). Accumulation and fragmentation of plastic debris in global environments. *Philosophical Transactions: Biological Sciences, 364*(1526), 1985–1998.

Beaumont, N. J., Aanesen, M., Austen, M. C., Börger, T., Clark, J. R., Cole, M., Hooper, T., Lindeque, P. K., Pascoe, C., & Wyles, K. J. (2019). Global ecological, social and economic impacts of marine plastic. *Marine Pollution Bulletin, 142*, 189–195. https://doi.org/10.1016/j.marpolbul.2019.03.022.

Beck, C. A., & Barros, N. B. (1991). The impact of debris on the Florida manatee. *Marine Pollution Bulletin, 22*(10), 508–510. https://doi.org/10.1011025-326X(91)90406-1.

Berry, F. S., & Berry, W. D. (1990). State lottery adoptions as policy innovations: An event history analysis. *American Political Science Review, 84*(2), 395–415.

Betsill, M., & Corell, E. (Eds). (2008). NGO diplomacy: The influence of nongovernmental organizations in international environmental negotiations. *Massachusetts Institute of Technology*.

Bornmann, L., & Mutz, R. (2015). Growth rates of modern science: A bibliometric analysis based on the number of publications and cited references. *Journal of the Association for Information Science and Technology, 66*(11), 2215–2222. https://doi.org/10.1002/asi.23329.

Bowley, J., Baker-Austin, C., Porter, A., Hartnell, R., & Lewis, C. (2020). Oceanic hitchhikers – Assessing pathogen risks from marine microplastic. *Trends in Microbiology*. https://doi.org/10.1016/j.tim.2020.06.011.

Browne, M. A., Dissanayake, A., Galloway, T. S., Lowe, D. M., & Thompson, R. C. (2008). Ingested microscopic plastic translocates to the circulatory system of the Mussel, *Mytilus Edulis (L)*. *Environmental Science & Technology, 42*(13), 5026–5031. https://doi.org/10.1021/es800249a.

Carpenter, E. J., & Smith, K. L. (1972). Plastics on the Sargasso Sea surface. *Science, 175*(4027), 1240–1241.

Choy, C. A., Robison, B. H., Gagne, T. O., Erwin, B., Firl, E., Halden, R. U., Hamilton, J. A., Katija, K., Lisin, S. E., Rolsky, C., & Houtan, K. S. V. (2019). The vertical distribution and biological transport of marine microplastics across the epipelagic and mesopelagic water column. *Scientific Reports, 9*(1), 7843. https://doi.org/10.1038/s41598-019-44117-2.

Clapp, J., & Swanston, L. (2009). Doing away with plastic shopping bags: International patterns of norm emergence and policy implementation. *Environmental Politics, 18*(3), 315–332. https://doi.org/10.1080/09640090902823717.

Cole, M., & Galloway, T. S. (2015). Ingestion of nanoplastics and microplastics by Pacific oyster larvae. *Environmental Science and Technology, 49*(24), 14625–14632. https://doi.org/10.1021/acs.est.5b04099.
Cózar, A., Martí, E., Duarte, C. M., García-de-Lomas, J., van Sebille, E., Ballatore, T. J., Eguluz, V. M., González-Gordillo, J. I., Pedrotti, M. L., Echevarría, F., Troublé, R., & Iriegoin, X. (2017). The Arctic Ocean as a dead end for floating plastics in the North Atlantic branch of the thermohaline circulation. Science Advances, 3(4), e1600582. https://doi.org/10.1126/sciadv.1600582.

Desforges, J.-P.W., Galbraith, M., & Ross, P. S. (2015). Ingestion of microplastics by zooplankton in the Northeast Pacific Ocean. Archives of Environmental Contamination and Toxicology, 69(3), 320–330. https://doi.org/10.1007/s00244-015-0172-5.

Ehrlich, P. R. (1968). The population bomb. Ballantine Books.

Engler, R. E. (2012). The complex interaction between marine debris and toxic chemicals in the ocean. Environmental Science and Technology, 46(22), 12302–12315. https://doi.org/10.1021/es3037105.

Erdogan, S., Yilmaz, I., Baybura, T., & Gullu, M. (2008). Geographical information systems aided traffic accident analysis system case study: City of Afyonkarahisar. Accident Analysis & Prevention, 40(1), 174–181. https://doi.org/10.1016/j.aap.2007.05.004.

European Parliament News. (2019). https://www.europarl.europa.eu/news/en-press-room/20190321IPR32111/parliament-seals-ban-on-throwaway-plastics-by-2021.

Friis, J. P. G. L., Otero, V., & Sobral, P. (2014). Evidence of microplastics in samples of zooplankton from Portuguese coastal waters. Marine Environmental Research, 95, 89–95. https://doi.org/10.1016/j.marenvres.2014.01.001.

Galloway, T. S., Cole, M., & Lewis, C. (2017). Interactions of microplastic debris throughout the marine ecosystem. Nature Ecology & Evolution, 1(5), 0116. https://doi.org/10.1038/s41559-017-0116.

Geyer, R., Jambeck, J. R., & Law, K. L. (2017). Production, use, and fate of all plastics ever made. Science Advances, 3(7), e1700782. https://doi.org/10.1126/sciadv.1700782.

Granek, E. F., Brander, S. M., & Holland, E. B. (2020). Microplastics in aquatic organisms: Improving understanding and identifying research directions for the next decade. Limnology and Oceanography Letters, 5(1), 1–4. https://doi.org/10.1002/loi2.10145.

Harris, L. S. T., & Carrington, E. (2019). Impacts of microplastic vs. natural abiotic particles on the clearance rate of a marine mussel. Limnology and Oceanography Letters, 5(1). https://doi.org/10.1002/loi2.10120.

Harris L. S.T., Gill, H., & Carrington E. (2021) Microplastic changes the sinking and resuspension rates of marine mussel biodioposes. Marine Pollution Bulletin 165112165–10. https://doi.org/10.1016/j.marpolbul.2021.112165

Haunschmid, R., Bornmann, L., & Marx, W. (2016). Climate change research in view of bibliometrics. PLoS ONE, 11(7), e0160393. https://doi.org/10.1371/journal.pone.0160393.

Jambeck, J. R., Geyer, R., Wilcox, C., Siegler, T. R., Perryman, M., Andrady, A., Narayan, R., & Law, K. L. (2015). Plastic waste inputs from land into the ocean. Science, 347(6223), 768–771. https://doi.org/10.1126/science.1260352.

Karaski, R., Vegg, T., Diana, Z., Bering, J., Caldas, J., Pickle, A., Rittchosf, D., & Virdin, J. (2020). 20 years of government responses to the global plastic pollution problem, 311.

Kenyon, K. W., & Kridler, E. (1969). Laysan Albatrosses swallow indigestible matter. The Auk, 86(2), 339–343. https://doi.org/10.2307/4083505.

Lacerda, A. L. D. F., dos Rodrigues, L. S., van Sebille, E., Rodrigues, F. L., Ribeiro, L., Secchi, E. R., Kessler, F., & Proietti, M. C. (2019). Plastics in sea surface waters around the Antarctic Peninsula. Scientific Reports, 9(1), 3977. https://doi.org/10.1038/s41598-019-40311-4.

Lam, C.-S., Ramanathan, S., Carbery, M., Gray, K., Vanka, K. S., Maurin, C., Bush, R., & Palanisami, T. (2018). A comprehensive analysis of plastics and microplastic legislation worldwide. Water, Air, and Soil Pollution, 229(11), 345. https://doi.org/10.1007/s11270-018-4002-z.

Li, J., Yang, D., Li, L., Jabeen, K., & Shi, H. (2015). Microplastics in commercial bivalves from China. Environmental Pollution, 207, 190–195. https://doi.org/10.1016/j.envpol.2015.09.018.

Li, J., Qu, X., Su, L., Zhang, W., Yang, D., Kolandhasamy, P., Li, D., & Shi, H. (2016). Microplastics in mussels along the coastal waters of China. Environmental Pollution, 214, 177–184. https://doi.org/10.1016/j.envpol.2016.04.012.

Mitchell, J. L. (2018). Does policy diffusion need space? Spatializing the dynamics of policy diffusion. Policy Studies Journal, 46(2), 424–451. https://doi.org/10.1111/psj.12226.

Mohn, L. B. (1969). Determinants of innovation in organizations. American Political Science Review, 63(1), 111–126.

Moore, D. A., & Carpenter, T. E. (1999). Spatial analytical methods and geographic information systems: Use in health research and epidemiology. Epidemiology Review, 21(2), 143–161. https://doi.org/10.1093/oxfordjournals.epirev.a017993 PMID: 10682254.

National Center for Ecological Analysis and Synthesis; NCEAS working group. (2011). Marine debris: Scale and impact of trash in ocean ecosystems. https://www.nceas.ucsb.edu/workinggroups/marine-debris-scale-and-impact-trash-ocean-ecosystems.

National Geographic. (2018). Planet or plastic. https://www.nationalgeographic.com/environment/planetplastic/.

Nanna B., Hartmann Thorsten, Hüffer Richard, Thompson Martin, Hassellöv Anja, Verschoor Anders E., Daugaard Sinja, Rist Therese, Karlsson Nicole, Brennholt Matthew, Cole Maria P., Herring Maren C., Hess Natalia P., Ivela Amy L., Lusher Martin, Wagner (2019) Are We Speaking the Same Language? Recommendations for a Definition and Categorization Framework for Plastic Debris. Environmental Science & Technology 53(3) 1039–1047 https://doi.org/10.1021/acs.est.8b05297

Ng, K. L., & Obbard, J. P. (2006). Prevalence of microplastics in Singapore’s coastal marine Environment. Marine Pollution Bulletin, 52(7), 761–767. https://doi.org/10.1016/j.marpolbul.2005.11.017.

Paul-Pont, I., Lacroix, C., González Fernández, C., Hégaret, H., Lambert, C., Le Goïc, N., Frère, L., Cassigne, A.-L., Sussarellu, R., Fabioux, C., Guyomarch, J., Albentosa, M., Huvet, A., & Soudant, P. (2016). Exposure of marine mussels Mytilus spp. to polystyrene microplastics: toxicity and influence on fluoranthene bioaccumulation.
Environmental Pollution. https://doi.org/10.1016/j.envpol.2016.06.039.

Pauna, V. H., Buonocore, E., Renzi, M., Russo, G. F., & Franzese, P. P. (2019). The issue of microplastics in marine ecosystems: A bibliometric network analysis. Marine Pollution Bulletin, 149, 110612. https://doi.org/10.1016/j.marpolbul.2019.110612.

Petrisor, A. I., Kawaguchi, T., & Decho, A. W. (2004). Quantifying CaCO3 microprecipitates within developing surface mats of marine stromatolites using GIS and digital image analysis. Geomicrobiology Journal, 21(8), 491–496. https://doi.org/10.1080/01490450490888037.

Plastics Europe. (2018). Plastics – The facts 2018. An analysis of European plastics production, demand and waste data.

Plastic Policy Inventory from Duke’s Nicholas Institute for Environmental Policy Solutions. (2020).

Powell, W. W., & Bromley, P. (2012). From smoke and mirrors to walking the talk: Decoupling in the contemporary world. The Academy of Management Annals, 6(1), 483–530. https://doi.org/10.1080/19416520.2012.684462.

Rios, L. M., Moore, C., & Jones, P. R. (2007). Persistent organic pollutants carried by synthetic polymers in the ocean environment. Marine Pollution Bulletin, 54(8), 1230–1237. https://doi.org/10.1016/j.marpolbul.2007.03.022.

Rogers, E. M. (1995). Diffusion of innovations (5th ed.). Free Press.

Ryan, P. G. (2015). A brief history of marine litter research. In Marine Anthropogenic Litter, Bergmann, M., Gutow, L., Klages, M., Eds. Springer International Publishing, pp 1–25. https://doi.org/10.1007/978-3-319-16510-3_1.

R Core Team (2019). R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. http://www.R-project.org/

Schnurr, R. E. J., Alboiu, V., Chaudhary, M., Corbett, R. A., Quanz, M. E., Sankar, K., Srain, H. S., Thavarajah, V., Xanthos, D., & Walker, T. R. (2018). Reducing marine pollution from single-use plastics (SUPs): A review. Marine Pollution Bulletin, 137, 157–171. https://doi.org/10.1016/j.marpolbul.2018.10.001.

Shipan, C. R., & Volden, C. (2008). The mechanisms of policy diffusion. American Journal of Political Science, 52(4), 840–857. https://doi.org/10.1111/j.1540-5907.2008.00346.x.

Shipan, C. R., & Volden, C. (2012). Policy diffusion: Seven lessons for scholars and practitioners. Public Administration Review, 72(6), 788–796.

Stern, P. C., Young, O. R., & Druckman, D. (Eds.). (1992). Global environmental change. National Academy.

Strickland, J. D. H., & Terhune, L. D. B. (1961). The study of in-situ marine photosynthesis using a large plastic bag. Limnology and Oceanography, 6(1), 93–96.

Surfrider Foundation. (n.d.). https://www.surfrider.org/initiatives/plastic-pollution. Accessed August 25, 2021.

Thompson, R. C., Olsen, Y., Mitchell, R. P., Davis, A., Rowland, S. J., John, A. W. G., McGonigle, D., & Russell, A. E. (2004). Lost at sea: Where is all the plastic? Science, 304(5672), 838–838.

Valente, T. W. (1995). Network Models of the Diffusion of Innovations. Hampton Press, Cresskill, NJ.

Wagner, T. P. (2017). Reducing single-use plastic shopping bags in the USA. Waste Management, 70, 3–12. https://doi.org/10.1016/j.wasman.2017.09.003.

Ward, J. E. (1996). Biodynamics of suspension-feeding in adult bivalve molluscs: Particle capture, processing, and fate. Invertebrate Biology, 115(3), 218–231. https://doi.org/10.2307/3226932.

Wikipedia. Phase-out of light weight plastic bags. https://en.wikipedia.org/wiki/Phase-out_of_lightweight_plastic_bags. Accessed April 2020.

World Wildlife Fund ReSource: Plastic activation hub. (n.d.). https://resource-plastic.com/. Accessed August 25, 2021.

Wright, S. L., Rowe, D., Thompson, R. C., & Galloway, T. S. (2013). Microplastic ingestion decreases energy reserves in marine worms. Current Biology, 23(23), R1031–R1033. https://doi.org/10.1016/j.cub.2013.10.068.

Xanthos, D., & Walker, T. R. (2017). International policies to reduce plastic marine pollution from single-use plastics (plastic bags and microbeads): A review. Marine Pollution Bulletin, 118(1), 17–26. https://doi.org/10.1016/j.marpolbul.2017.02.048.

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