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Blettler, Martín C.M.; Abrial, Elie; Khan, Farhan R.; Sivri, Nuket; Espinola, Luis A.

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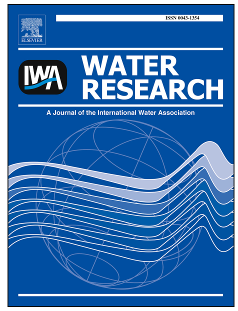

Freshwater plastic pollution: Recognizing research biases and identifying knowledge gaps

Martín C.M. Blettler, Elie Abrial, Farhan R. Khan, Nuket Sivri, Luis A. Espinola

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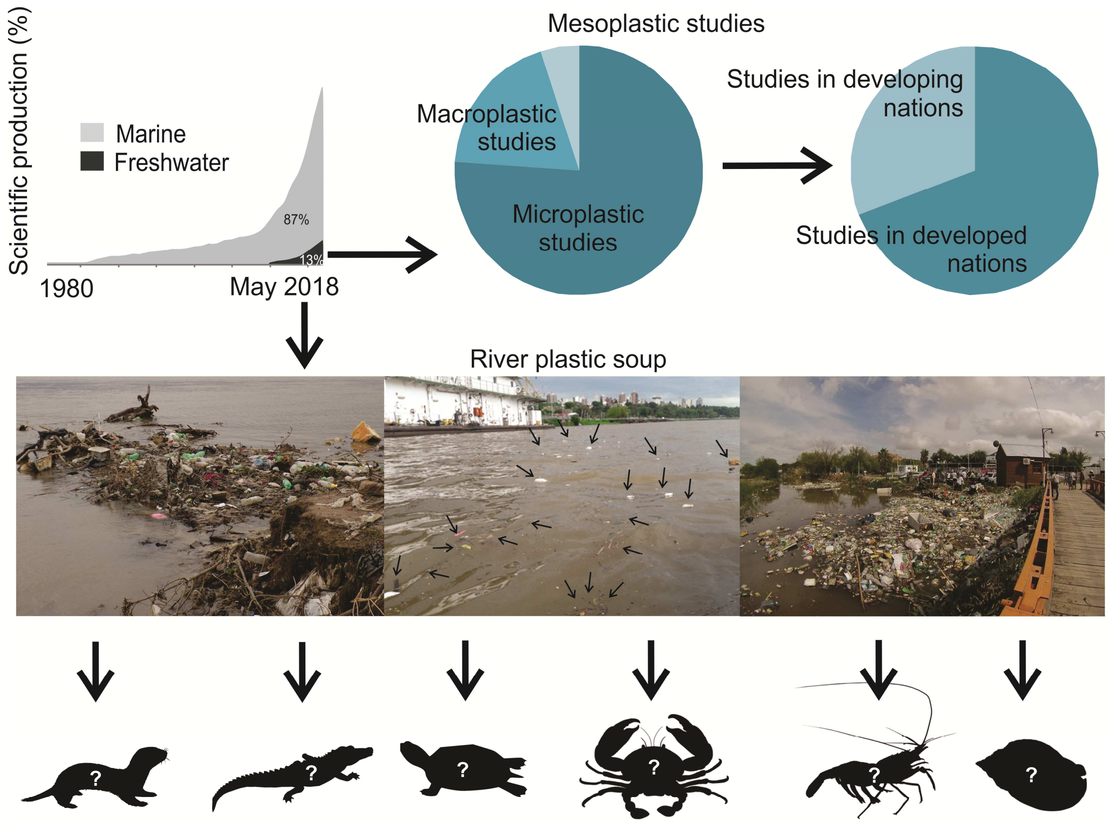
Scientific production (%)
Marine
Freshwater
87%
13%
1980
May 2018
Mesoplastic studies
Macroplastic studies
Microplastic studies
Studies in developing nations
Studies in developed nations
River plastic soup
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Title

Freshwater plastic pollution: recognizing research biases and identifying knowledge gaps

Authors

Martín C. M. Blettler[1]

Elie Abrial[1]

Farhan R. Khan[2]

Nuket Sivri[3]

Luis A. Espinola[1]

[1]Instituto Nacional de Limnología (INALI; CONICET-UNL), Ciudad Universitaria (3000), Santa Fe, Argentina. Correspondence to: mblettler@inali.unl.edu.ar.

[2]Department of Science and Environment, Roskilde University, Universitetsvej 1, PO Box 260, DK-4000 Roskilde, Denmark.

[3] Istanbul University, Cerrahpasa, Engineering Faculty, Department of Environmental Engineering, Istanbul, 34320, Turkey.

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Abstract

The overwhelming majority of research conducted to date on plastic pollution (all size fractions) has focused on marine ecosystems. In comparison, only a few studies provide evidence for the presence of plastic debris in freshwater environments. However, owing to the numerous differences between freshwater studies (including studied species and habitats, geographical locations, social and economic contexts, the type of data obtained and also the broad range of purposes), they show only fragments of the overall picture of freshwater plastic pollution. This highlights the lack of a holistic vision and evidences several knowledge gaps and data biases. Through a bibliometric analysis we identified such knowledge gaps, inconsistencies and survey trends of plastic pollution research within freshwater ecosystems.

We conclude that there is a continued need to increase the field-data bases about plastics (all size fractions) in freshwater environments. This is particularly important to estimate river plastic emissions to the world's oceans. Accordingly, data about macroplastics from most polluted and larger rivers are very scarce, although macroplastics represent a huge input in terms of plastics weight. In addition, submerged macroplastics may play an important role in transporting mismanaged plastic waste, however almost no studies exist. Although many of the most plastic polluted rivers are in Asia, only 14% of the reviewed studies were carried out in this continent (even though the major inland fisheries of the world are located in Asia's rivers). The potential damage caused by macroplastics on a wide range of freshwater fauna is as yet undetermined, even though negative impacts have been well documented in similar marine species. We also noted a clear supremacy of microplastic studies over macroplastic ones, even though there is no reason to assume that freshwater ecosystems remain unaffected by macro-debris.

Finally, we recommend focusing monitoring efforts in most polluted rivers worldwide, but particularly in countries with rapid economic development and poor waste management.

1. Introduction

The presence of plastic debris has become a well-researched "hot topic" in the marine environment, but up until recently was ignored in freshwater environments (Wagner et al., 2014; Eerkes-Medrano et al., 2015). While plastic pollution monitoring data from freshwater environments is still in its infancy, there is evidence showing plastic presence within such ecosystems since many years ego (e.g. Williams and Simmons, 1996), and even within pristine and remote locations (e.g. Free et al., 2014). The majority of plastic debris is used and disposed of on land, both terrestrial and adjacent freshwater environments are subject to extensive pollution by plastics resulting from large amounts of human litter (Horton et al., 2017). Similar to marine systems, major plastic pollution contributions emanate from cities, poor waste management practices, fly tipping, improper disposal or loss of products from industrial and agricultural activities, debris from the discharge of untreated sewage, and storm water discharges, which also sweeps litter collected in storm drains into the rivers (van der Wal et al. 2015; González et al. 2016). As a result, concerns about the impact of plastics on freshwater ecosystems are legitimate and should receive more scientific attention (Eerkes-Medrano et al., 2015; Lebreton et al., 2017; Li et al., 2017).

The limited information, however, has revealed that the abundance of microplastics is comparable to marine contamination levels (Peng et al., 2017). Such abundance could likely lead to plastic ingestion by the biota. Studies have reported plastic ingestion by wild freshwater organisms (e.g. Sanchez et al., 2014; Faure et al., 2015; Biginagwa et al., 2016; Pazos et al., 2017). Plastic concentrations have been reported in rivers (e.g. Lechner et al., 2014; Klein et al., 2015), lakes (e.g. Fischer et al., 2016; Blettler et al., 2017), estuaries (e.g. Peng et al., 2017) and even on wastewater treatment plants (e.g. Mintenig et al., 2017; Correia Prata, 2018). However, even a brief examination of this freshwater plastics literature is enough to perceive that it is still scarce and does not appear to be in accordance with global environmental priorities, endangered species, or social demands. Moreover, freshwater plastic research seems to be inherently biased towards a country's state of development and disconnected as each study was conceived and conducted with its own specific aims in mind.

In the present study we employed a bibliometric analysis of paper on the topic of freshwater plastic pollution and compared it to the abundant literature on marine environments. Through our analysis we thus identify knowledge gaps and research biases in freshwater plastic pollution literature; for example, type of data urgently required, freshwater environments and fauna with no available data to date and missing ecological impacts. Finally, we make a number of specific suggestions to fill these knowledge gaps.

2. Methodology

The searching methodology (and criteria) was divided into two. On one side, a restricted searching (using only one search engine and restrictive keywords) was conducted to compare the relative scientific production in marine and freshwater environments (2.1). On the other side, an unrestricted searching (using a broad range of search engines and keywords) was performed in order to detect as many papers as possible regarding plastic pollution in freshwater systems (2.2).

2.1. *Marine versus freshwater literature comparison (restricted searching).*

This literature review was exclusively based on the Scopus search engine (https://www.scopus.com) due to the great amount of marine literature. Scopus is a bibliographic database of academic journal articles, covering nearly 20,000 titles of peer-reviewed journals from over 5,000 publishers.

2.1.1. *Searching criteria.*

We defined the Scopus search as follows: i) for marine environments: TITLE-ABS-KEY (“plastic pollution” OR “plastic contamination” OR “plastic debris” AND sea OR coastal OR marine OR maritime OR ocean). ii) For freshwater systems: TITLE-ABS-KEY (“plastic pollution” OR “plastic contamination” OR “plastic debris” AND freshwater OR river OR lake OR estuary OR stream). No limits in years (until May 2018) and subject area were considered. However, reviews, opinion papers (no field-data), book chapters, conference papers and scientific reports were excluded from the analysis.

2.2. *Freshwater literature unrestricted searching.*

We census and compiled all available scientific literature about plastic pollution in freshwater environments using the following search engines: Scopus dataset (see above), Google Scholar (http://scholar.google.com/), GetCITED (http://www.getcited.org/), PLOS ONE (http://www.plosone.org/), BioOne (http://www.bioone.org/) and ScienceDirect (http://www.sciencedirect.com/).

2.2.1. *Searching criteria.*

The selected criteria of search included related words like: “freshwater”, “inland water”, “continental water”, “river”, “stream”, “creek”, “brook”, “lake”, “lagoon”, “pond”, “wetland”, “estuary”, “reservoir”, “sewage”, “laboratory condition” AND “plastic”, “macroplastic” (i.e. ≥ 2.5 cm), “mesoplastic” (i.e. 2.5 – 0.5 cm), “microplastic” (i.e. ≤ 0.5 cm) AND “pollution”, “contamination”, “ingestion”, “entanglement”, “waste”, “debris”. We also included herein book chapters, conference papers and scientific reports but reviews and opinion papers were excluded from the analysis (no field-data). No limits in years (until May 2018), document type and subject area were considered.

2.3. *Quality assessment and categorization.*

Subsequently, an exhaustive manual checking of the results (paper by paper) was performed to both searches (sections 2.1 and 2.2) at the discretion of the authors of this study. This individual manual checking was crucial to avoid study repetitions (for example, advanced results published in congress but then fully published in journals), papers outside the topic of this study, unclear or incomplete reports, etc. This step significantly reduced the final data-set showing that keywords themselves do not necessary represent a reliable search parameter.

From each of the reviewed papers we identified: i) aquatic environment (marine or freshwater); ii) authors; iii) country and development indicators (based on the World Bank list of economies, 2017); iv) plastic size fraction (micro, meso, and macroplastics) (note: studies can consider both one or more fractions); v) freshwater environment (river, lake, estuary, reservoir, sewage and laboratory condition); vi) compartment (water surface or column, shoreline or bottom sediments); vii) biota impact/interaction; and viii) biotic community (fish, bird, mammal, reptilian, zoobenthos, zooplankton, mollusk, bacteria, etc).

2.4. *Data analyses.*

The information was organized as a unique data-set. In order to compare studies in marine and freshwater systems the cumulative number (%) and rate of growth (articles year-1) of the scientific production were estimated for both environments. This rate of growth was calculated from 2010 to date. Simple statistics were used in order to create maps, tables and figures identifying countries and regions that have been studied and those where research has not yet been conducted, impacted biota in marine and freshwaters, plastic size fractions in freshwater systems, studied freshwater environments and compartments. Major plastic polluting rivers were also identified in relation to fisheries production and the lack of field data.

3. Results and discussion

3.1. Bias in marine and freshwater scientific production.

A total of 624 papers were found for marine environments based on the Scopus searching (see section 2.1). However, only 440 (~70%) of them were suitable for the purposes of this study (selected under authors' criterium). In order to keep comparable search criteria, a similar analysis was carried out for freshwater literature (i.e. Scopus searching) with a total of 105 papers identified, but only 64 of them were appropriate to be used in this study.

While the number of published studies on plastic pollution in marine environments has increased dramatically in the last decades, considerably less studies have assessed this topic within freshwater systems. While this tendency has been suggested by other authors (Wagner et al., 2014; Eerkes-Medrano et al., 2015; Blair et al. 2017), it has not been fully quantified thus far. We found that 87% of plastic pollution studies are related to the marine environments and only 13% to freshwater systems, with a rate of growth of approximately 41 *vs*. 7 papers $year^{-1}$ for marine and freshwater environments, respectively (Figure 1).

>>>>> Figure 1.

Thus, the rate of growth in marine scientific production is more than 5 times higher than in freshwater ecosystems. Evidently, scientific efforts are still too focused on marine environments. The limited information, however, suggests that plastic pollution in freshwater systems is comparable to marine contamination levels. While diminishing aesthetic value of rivers and lakes, plastic debris is also likely to cause freshwater biodiversity loss and pose threats to human health through fish and water consumption (Peng et al., 2017; Tyree and Morrison, 2017). In this context, there is no reason that justifies the continued lack of studies in freshwater environments.

3.2. Bias in Global coverage.

In addition to the 64 papers found for freshwater plastic research using Scopus, 42 peer reviewed publications papers were found using different search engines (see section 2.2). Thus, a total of 106 plastic pollution studies were recorded in freshwater environments worldwide. These studies were distributed between 23 total countries with 73 studies carried out in developed countries and 33 in developing ones (Figure 2).

>>>>> Figure 2.

Figure 2 revealed that data on freshwater plastics is fragmented across continents and completely absent from the majority of countries. Most of the studies were performed in Europe and North America (67%). Only a few studies were detected in Asia (most of them in China; 16%), South America (Brazil, Argentina, Colombia and Chile; 11.8%), Africa (South Africa and Tanzania; 4%) and Australia (2%; Figure 2). China is the second most dominant country in terms of scientific production (and by far the leading of the fast developing countries). However, its scientific effort is still poor considering China's population (1.41 billion, based on United Nations statistics), total area (9,597 M km²), GDP Annual Growth Rate (the Chinese economy expanded by 6.8 percent year-on-year in the first quarter of 2018, the same pace as in the previous two quarters; World Bank open data, 2018) and mainly the fact that 7 of the world's top 20 of the reported plastic polluted rivers flow through major Chinese cities. Models suggest that only these Chinese rivers contribute around two thirds of plastic released through rivers into the oceans (Lebreton et al., 2017). Moreover, according to our review, there is no field data about notable Asian rivers, such as the Ganges and Mekong Rivers, that are likely polluted by plastics.

According to the international literature, reviews about plastic pollution in freshwaters has been conducted by Wu et al. (2018) in Asia, Khan et al. (2018) in Africa, Eerkes-Medrano et al. (2015) and Breuninger et al. (2017) in North America and Europe, among others. However, an overview of plastics in South America has been absent from the literature until now. Available publications in this continent are: Costa et al. (2011), Possatto et al. (2011), Ramos et al. (2012), Dantas et al. (2012) and Ivar do Sul and Costa (2013) in Brazil; Acha et al. (2003), Blettler et al. (2017) and Pazos et al. (2017) in Argentina; Correa-Herrera et al. (2017) and Arias-Villamizar and Vazquez-Morillas (2018) in Colombia; and Rech et al. (2015) in Chile. Through the analysis of these papers, we detected that 5 studies focused on microplastic ingestion by fish, and 8 of them selected estuaries as studies area. Microplastic ingestion by fish was the most selected topic of study in South America. While fish were clearly impacted by plastic pollution (e.g. Pazos et al., 2017), no other aquatic taxa were study in South America. Considering that 5 of the top 10 largest river in the world belong to South America and their drainage areas combined represent 9,650 x 103km^2, with a mean annual discharge of 262,000 m^3s^{-1} to the ocean, and a population that far exceed 100 M of habitants, we alleged an unjustified lack of attention to this continent.

In short, from a total of 195 countries in the world only 23 have studied the plastic pollution in freshwater systems. Therefore, we suggest that the existing information is still fragmentary and biased by countries development level and not by environmental global necessities.

3.3. Bias between research in developed and developing countries.

Sixty-nine percent of the recorded studies were carried out in developed countries and the 31% remaining in developing ones (Table 1). Research on freshwater plastic pollution is a relatively new topic and most efforts have been carried out in industrialized countries (Figure 2). This level of disparity is not surprising since in the rankings of the top 10 best nations in sciences only one is an emerging economy (China; The Editors, 2017). However, this unbalance is particularly significant from an environmental and social point of view, since waste collection, processing and final waste disposal still represents a problem in many low-middle income countries (Mohee et al., 2015).

>>>>> Table 1.

Increasing population levels, booming economy, rapid urbanization and the rise in community living standards have greatly accelerated the municipal solid waste generation rate in developing countries (Minghua et al., 2009). According to reports published by United Nations (United Nations Human Settlements Programme, 2016) and the World Bank (Hoornweg et al., 2012), the systems used for solid waste management in least developed countries are not fully suitable to handle the current and future volume of waste generation. This is particularly true in urban informal settlements, which are often in the most hazardous locations such as river floodplains. Open uncontrolled dumping is still the most common method of solid waste disposal in such countries, from which plastics can be introduced into water bodies. This is particularly significant since the greater inland fisheries are located in developing countries (with the exception of the Russian Federation; Table 2).

>>>>> Table 2.

The largest fish production in the world is placed in China by far (FAO, 2016). This is followed by India, Bangladesh, Myanmar and Cambodia. All these fisheries belong to Asia, but our analysis shows an apparent lack of field studies evaluating the effect of plastic pollution on fish in these polluted rivers (Table 2). Note that 18 of the top 20 plastic polluted rivers, from global models of plastic load inputs, are located in the major inland fish producer countries. In addition, the 16 countries listed in this table represent 80% of the total inland waters fish capture production around the world (FAO, 2016). Inland fisheries are extremely important since hundreds of millions of people around the world benefit from low-cost protein, recreation, and commerce provided by them, particularly in developing countries where alternative sources of nutrition and employment are scarce (McIntyre et al., 2016). Table 2 shows some crucial facts: i) the greater inland fisheries are located in developing countries of Asia (mainly in China and India); ii) the major inland fisheries are located in the top 20 plastic polluted rivers (as estimated by Lebreton et al. 2017, through global models of plastic load inputs), with the exception of the Magdalena (Colombia) and the Tamsui Rivers (Taiwan); iii) there is a clear lack of field evidence about the effect of plastic pollution on fish in the most polluted rivers. These facts reveal a double problem. Firstly, the top 20 plastic polluted rivers (as modeled by Lebreton et al., 2017) are located in the major inland fisheries (belonging to developing countries, particularly Asia's economies). Secondly, a few field studies evaluating the impact of microplastics on fish for consumption is definitely not enough considering the human health and economic implications.

The above emphasises the need to focus monitoring and mitigation efforts in polluted rivers, particularly in countries with rapid economic development, large inland fisheries and poor waste management.

Finally, a worrying level of plastic pollutants was found inside fish in the few rivers where plastic ingestion was studied (e.g. Pazos et al., 2017). In this sense, we hypothesize that fish from the rivers mentioned in the Table 2 could be contaminated by plastics as well. As a result, there is an urgent need to study plastic impact on fisheries given the economic importance and threats on human health.

3.4. Bias in species selection.

The impact of plastic pollution on biota has been better studied in marine environments, involving many biotic groups and species (particularly birds; Table 3). From a total of 440 recorded studies in marine environments 178 (i.e. 40.5%) focused on impacts (or interactions) of plastic debris with aquatic organisms, whereas 35 of the 106 recorded studies in freshwater systems (i.e. 33%) analyzed the similar plastic-biota interactions in freshwaters (Table 3).

>>>>> Table 3.

Plastic research in the marine environment has focused on a wide range of organisms; birds (e.g. Wilcox et al., 2015), fish (e.g. Steer et al., 2017), mammals (e.g. Garrigue et al., 2016), reptiles (e.g. Schuyler et al., 2015), mollusks (e.g. Silva et al., 2016), decapods (e.g. Murray and Cowie, 2017), bacteria (e.g. Keswania et al., 2016), algae (e.g. Yokota et al., 2017), and fungus (e.g. Paço et al., 2017). However, Table 3 evidences the few studies evaluating impacts on freshwater fauna. Only a few studies in freshwater fish, birds, bacteria (attached to micro-particles of plastics), mosses, algae and invertebrates are available. Studies on microplastic ingestion by fish prevail in developing countries (which is consistent with our previous results; Table 2). However the other taxa were mainly studied in the developed world (Table 3). The recent interest of emerging economies in the impact of plastic pollution on fish could be explained by the magnitude that inland fisheries have in such economies (FAO, 2016). Artisanal and small-scale fisheries play a crucial role as a source of livelihoods, food security and income for millions of people, particularly from developing countries (Berkes et al., 2001) (see section 4.3). More than 90% of the output of inland fisheries comes from developing countries and only 3.5% from industrial countries (Smith et al., 2005). Researchers from developing economies are likely aware of this and accordingly focus their studies in the impact of microplastics on fisheries.

No studies evaluating macroplastic impact/interaction on freshwater fauna (for example by entanglement or as building material of bird nests) were recorded (Table 3). However, entanglement of marine species in marine debris is a global problem affecting at least 200 species of mammals, sea turtles, sea birds, fish and invertebrates (NOAA, 2014). This reveals a lack of attention on macroplastics since examples of this type of interactions are visually obvious, particularly in emerging countries where solid waste management are not well considered, as mentioned above (Abarca-Guerrero et al., 2013).

3.5. Bias in size fraction reporting.

Referring to the size-ranges, plastic debris is commonly termed as micro- (≤5 mm), meso- (5 mm-2.5 cm) or macroplastic (> 2.5 cm; Lippiatt et al., 2013), but there is not a standardized definition. With regard the size fraction investigated amongst the different studies 76% of the surveys in freshwater systems have studied microplastics, 19% macroplastics and only 5% mesoplastics (Table 1). While some studies pay attention to the three size-ranges, most of them (65%) have exclusively focused on microplastics (i.e. deliberately ignoring macro and meso-debris) and only 7% entirely on macroplastics (ignoring micro and meso-fractions). Studies on mesoplastics (excluding macro and micro-debris) were not found.

Similar trends are seen in terms of global biases within the different size classes. Of all the freshwater research surveyed for this paper, microplastics were most commonly investigated in the developed and developing world (53% and 23% of the studies, respectively; Table 1). Similarly, macroplastic surveys accounted for 14% in developed countries and only 5% in developing ones. Considering the mismanagement of solid waste in least developed economies, which often end up in water bodies as bottles, bags and packaging (section 3.3), the mentioned 5% represents another bias in the current knowledge.

Additionally, many microplastic studies defined in this study as "non-exclusive" (Table 1) report macroplastics (e.g. Moore et al., 2011; Sadri and Thompson, 2014; Baldwin et al., 2016; Cable et al., 2017), but acknowledge the limitations in accurately quantifying these types of plastics since the sampling designs of these studies were not specifically adapted to macroplastics. The relatively small nets cross-sectional sampling areas and short exposure times may not be appropriate to representatively capture macroplastic concentration.

Based on this literature review we suggest that the dominance of microplastic studies over macroplastic ones could be explained by: 1) microplastics have been identified as one of the top 10 emerging issues by the United Nations Environment Programme (UNEP) in the 2005, 2014 and 2016 Year Books, which possibly encouraged microplastic studies. For example, Eerkes-Medrano et al. (2015) and Gil-Delgado et al. (2017) explicitly mentioned this reason to justify their size-range selection. 2) It has been proved that microplastics can impact freshwater fish (e.g. Lechner et al., 2014; Sanchez et al., 2014; Biginagwa et al., 2016; Pazos et al., 2017), birds (Faure et al., 2012; Holland et al., 2016; Gil-Delgado et al., 2017) and even zooplankton organisms (Rosenkranz et al., 2009), which is economic and ecologically relevant. 3) Small plastic fragments may possibly have leaching rates of exogenous chemicals (trace metals and organic pollutants) higher than those given by macroplastics, due to their proportionally greater surface (Nakashima et al., 2012). Finally, 4) microplastics are possible more widespread than macroplastics (Lithner, 2011). These four reasons could explain why microplastics have received more attention than macroplastics by scientists. However, we identified three reasons for the significance of macroplastics in freshwaters, and which support further research: 1) over one hundred species of marine vertebrates have been recorded as entangled in macroplastic debris (Allen et al., 2012; NOAA, 2014) such as pinnipeds (Hanni and Pyle, 2000), sharks (Sazima et al., 2002), grey seals (Allen et al., 2012), turtles and seabirds (using plastic garbage as nesting material) (de Souza Petersen et al., 2016). No studies have been carried out describing macroplastics interaction/impact on freshwater fauna (see section 4.4). Additionally, plastic bags, bottles, packaging straps and fishing lines in oceans are the most common items which researchers have reported animals entangled in (Raum-Suryana et al., 2009; Allen et al., 2012). All these macro-items are dominant in bottom sediments (Morritt et al., 2014), shoreline sediments (e.g. Blettler et al., 2017) and water surface (e.g. Gasperi et al., 2014) of freshwater environments worldwide. This suggests that fluvial species can be likewise impacted by macro-debris. 2) Recently, pioneer studies have estimated the amount of plastic exported from river catchments into the sea (Lebreton et al., 2017; Schmidt et al., 2017). Given the reduced field-data in rivers, clearly identified in this study (Figures 1 and 2; Tables 1, 2 and 3), these authors developed models based on mismanaged plastic waste, population density and hydrological data in river catchments. The methodological strategy followed by these studies evidenced the scarcity of river field-data collections, preventing direct estimations. Macroplastic data could be more important than microplastic data for this type of studies, since macroplastics represent a significantly greater input in terms of plastics weight (more than 100 times according to Schmidt et al., 2017). Lastly, 3) microplastic surveys not necessarily are surrogate for macroplastic ones. Even when some authors found a predictive relationship between micro and macroplastic items (e.g. Lee et al. 2013 on marine marshes and beaches; González et al. 2016 on rivers); others reported no-associations between both size particles, either in number or in resin composition (e.g. Blettler et al., 2017 in freshwater lakes). Thus, macroplastics appear to have a particular distribution, potentially affecting different habitat and species than microplastics, justifying its separate study.

These factors highlight the urgent requirement to increase the field-data bases about macroplastics in freshwater environments, particularly in lotic environments of developing countries. We warn about the necessity to fill this knowledge gap, given the potential damage caused by macroplastics in freshwater environments.

3.6. Bias in habitat diversity.

The selected abiotic compartment of each paper was disproportionally represented amongst freshwater systems (Table 4). However, research efforts on plastic pollution seem to be relatively well distributed between rivers (31%), lakes (29.2%) and estuaries (21.2%).

>>>>> Table 4.

Conversely, studies in reservoir are an evident minority (only 1.8% and exclusively located in China). Considering that about 16.7 million dams (with reservoirs larger than 0.01ha) exist worldwide (Lehner et al., 2011) and 50% of larger rivers are affected by large dams (e.g. in rivers such as the Upper Paraná River in Brazil contain more than 130 major dams) this deficiency should be rectified.

Water surface and shoreline sediments were the most common abiotic compartment where plastic accumulation was studied in freshwater systems. Both compartments represent more than 75% of the studies (Table 4). Few studies have sampled plastic debris in the water column or in/close to the bottom sediments. However, Morritt et al. (2014) focusing on the River Thames (London, United Kingdom) demonstrated that a large unseen volume of submerged plastic is flowing along river beds, representing an additional significant input which has been underestimated.

4. Conclusions and recommendations

Through analysis of the scientific literature pertaining to the presence of plastic debris in the freshwater environments we identify an urgent need to increase the overall knowledge of this research area. We quantitatively confirmed the dominance of plastic pollution studies in marine environments over freshwater-focused research. Concerns about the impact of plastics on freshwater ecosystems were legitimated through this review, as well as more opinion-orientated publications, and therefore it must receive more scientific attention. Notably, we detected biases in where and how studies are conducted that do not necessarily correlate to levels of expected pollution or environmental priorities. Such biases likely result from socio-economic differences between developed and developing nations. Furthermore, we also detected biases in the species used as proxies for environmental monitoring, biases in habitat selection and biases in size-fraction monitoring. Such partialities seen to be more related to authors' subjectivity than environmental necessities. Six specific findings are outlined below with recommendations to rectify these knowledge gaps.

1) The majority of plastic pollution studies in freshwaters were carried out in Europe (Western-Central Europe) and North America (United State and Canada). However, it is necessary to enlarge the scientific efforts in Asia and South America, particularly in low-middle income countries. Increasing population levels, booming economy and rapid urbanization have greatly accelerated the plastic waste generation rate, while treatment, recycle alternatives, recovery routes and final disposal are still deficient in many developing countries within these continents.

2) The major inland fisheries (belonging to developing countries, particularly Asia's economies) are located in the top 20 plastic polluted rivers. However, extremely few field-data or studies evaluating plastic impact on fisheries are available from these rivers. There is an urgent need to focus

monitoring and mitigation efforts in the most polluted rivers or where inland fisheries are crucial for local consumption and economies.

3) Unlike in marine, we detected a lack of studies analyzing the impact of microplastic pollution on freshwater mammals, reptiles, macrocrustaceans and bivalves. Similarly, no studies evaluating macroplastics impact (or interaction) on freshwater fauna (e.g. by entanglement or as building material of bird nests) were recorded. Both observations suggest, once again, the limited development of freshwater research.

4) We detected a dominance of microplastic studies over macroplastic studies in freshwater environments worldwide, even though there is no reason to assume that these ecosystems remain unaffected by macro-debris. In addition, assuming that rivers may play an important role in transporting mismanaged plastic waste from land into the ocean, measurements of river macroplastic debris are urgently required. Likewise, submerged macroplastics flowing near to the river bed should be also quantified to avoid underestimations.

5) In the context of the global boom in hydropower dam construction worldwide (particularly in developing countries), studies evaluating plastic pollution are essential to understand its potential for reservoirs to act as garbage retainers.

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Figure captions

Figure 1. Comparison between plastic pollution studies performed in marine and freshwaters, showing total scientific publication and rate of growth in both environments since January 1980 to May 2018.

Figure 2. World map showing number of studies about freshwater plastic pollution per country. Color scale: dark blue to light blue scale stand for more to less number of studies. Where, United States (US): 18; China (CN): 14; United Kingdom (UK): 13; Germany (DE): 9; Italy (IT): 7; Canada (CA): 7; Brazil (BR): 6; France (FR): 5; Austria (AT): 4; Argentina (AR): 3; Netherland (NL): 3; Switzerland (SW): 3; South Africa (ZA): 3; Australia (AU): 2; Colombia (CO): 2; Denmark (DK): 1; Spain (ES): 1; Tanzania (TZ): 1; Chile (CL): 1; Mongolia (MN): 1; India (IN): 1; Vietnam (VN): 1; and Sweden (SE): 1 study. “-p”: plastic. Note: exceptionally some studies covered more than one country.

Table 1. Percentage of freshwater studies carried out in developed and developing countries to each plastic size fraction. And percentage of macro, meso and microplastic studies in freshwater environments, detailing percentage of papers considering only one "exclusive" fraction size (i.e. one merely plastic size fraction was studied) and more than one fraction size ("non-exclusive").

Country development	Total (%)	Size fraction	Studies (%)	Size fraction	Total per size fraction (%)	Type	Studies (%)
Developed	69	Microplastic	53	Microplastic	76	Exclusive	57
		Macroplastic	14			Non-exclusive	16
		Mesoplastic	2	Macroplastic	19	Exclusive	6
Developing	31	Microplastic	23			Non-exclusive	15
		Macroplastic	5	Mesoplastic	5	Exclusive	0
		Mesoplastic	3			Non-exclusive	6

Table 2. Major inland fisheries producer countries in relation with the most plastic polluted rivers and field studies about fish plastic ingestion. *FAO (2016); **Lebreton et al. (2017).

Major inland fish producer countries	Fish capture, period 2003-2014 (average tones)*.	Top 20 plastic polluted rivers per country (ranking number)**.	Field studies evaluating plastic ingestion by fish.
China	2,229,652	Yangtze (1), Xi (3), Huangpu (4), Mekong (11), Dong (13), Zhujiang (17), Hanjiang (18)	2 (Taihu Lake in the Yangtze Delta)
India	1,017,539	Ganges (2)	0
Bangladesh	969,273	Ganges (2)	0
Myanmar	867,435	Irrawaddy (9), Mekong (11)	0
Cambodia	398,896	Mekong (11)	0
Uganda	398,646	-	0
Indonesia	339,872	Brantas (6), Solo (10), Serayu (14), Progo (19)	0
Tanzania UR	305,854	-	1 (Victoria Lake)
Nigeria	269,717	Cross (5), Imo (12), Kwa Ibo (20)	0
Egypt	256,437	-	0
Brazil	242,148	Amazon (7)	4 (Goiana Estuary)
Russia	231,044	-	0
Congo DR	224,930	-	0
Thailand	212,455	Mekong (11)	0
Viet Nam	199,306	Irrawaddy (9), Mekong (11)	0
Philippines	174,585	Pasig (8)	0

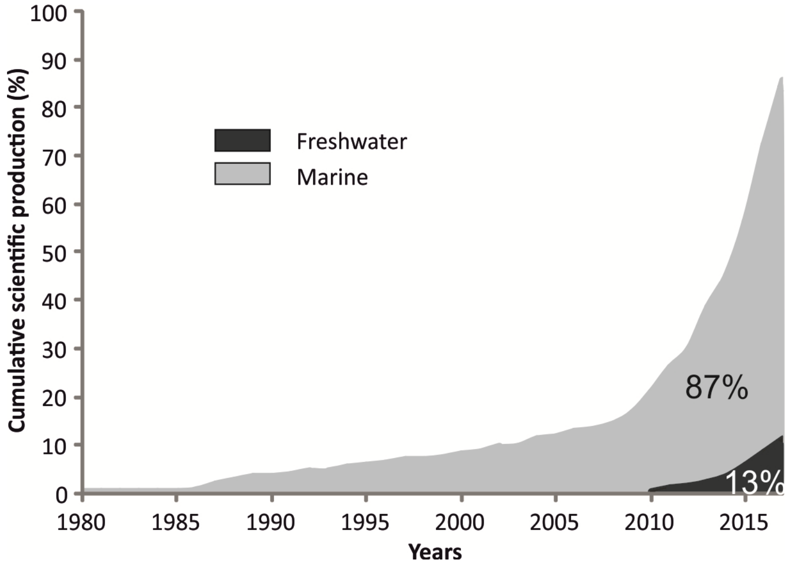
Table 3. Marine and freshwater studies considering impacts and interactions between plastics and organisms. [1]Biotic groups impacted by macroplastics (entanglement). [2]Macroplastics used as building material by birds. [3]Scopus searching (see Methodology). [4]Unrestricted searching (see Methodology; 2.2). Note: some studies covered more than one fauna group.

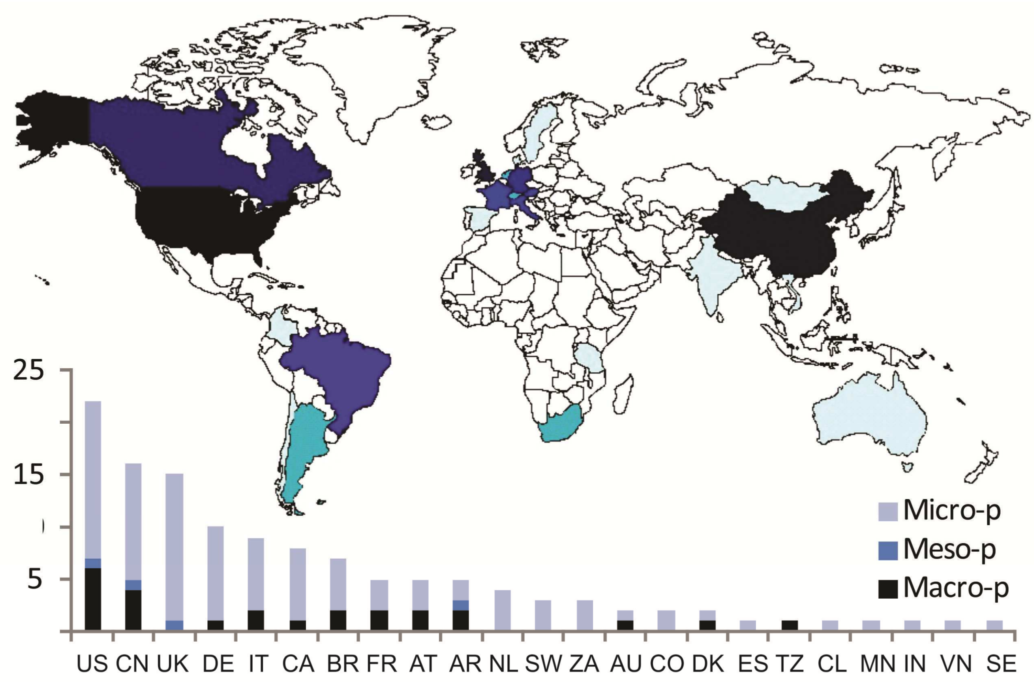
	N° of studies		
Biotic groups	Marine	Freshwater	
		Developed countries	Developing countries
Fish	35	10	7
Bird[1; 2]	59	3	1
Mammal[1]	11	0	0
Turtle	17	0	0
Zoobenthos	15	3	1
Zooplankton	7	7	0
Mollusk	10	1	0
Decapods	4	0	0
Bacteria	13	3	0
Fungi	1	0	0
Alga	6	2	0
Moss	0	1	0
Total studies	178 (40.5%)	35 (33%)	
n= 440 (marine[3]) studies; n= 106 (freshwater[4])			

Table 4. Percentage of studies classified according to the freshwater environment and the abiotic compartment. Where: s= sediments; w= water.

	Environment					
	River	Lake	Estuary	Laboratory	Sewage	Reservoir
N° of studies (%)	31	29.2	21.2	11.5	5.3	1.8

	Abiotic compartment			
	W. surface	Shoreline s.	Bottom s.	W. column
N° of studies (%)	45.7	30.9	12.3	1.11


Cumulative scientific production (%)
100
90
80
70
60
50
40
30
20
10
0
1980
1985
1990
1995
2000
2005
2010
2015
Years
Freshwater
Marine
87%
13%



25
15
5
Micro-p
Meso-p
Macro-p
US CN UK DE IT CA BR FR AT AR NL SW ZA AU CO DK ES TZ CL MN IN VN SE

Highlights

1) There is a dominance of plastic pollution studies in marine over freshwater systems.

2) Of the existing freshwater studies, most come from developed countries.

3) Plastic pollution in the main inland fisheries rivers remains nearly unstudied.

4) We detected an evident supremacy of microplastic over macroplastic studies.

5) We identified the freshwater fauna groups not yet studied.