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# **Foraminifera and plastic pollution: knowledge gaps and research opportunities**

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## ABSTRACT

Plastic has become one of the most ubiquitous and environmentally threatening sources of pollution in the Anthropocene. Beyond the conspicuous visual impact and physical damages, plastics both carry and release a cocktail of harmful chemicals, such as monomers, additives and persistent organic pollutants. Here we show through a review of the scientific literature dealing with both plastic pollution and benthic foraminifera (Rhizaria), that despite their critical roles in the structure and function of benthic ecosystems, only 0.4% of studies have investigated the effects of micro- and nano-plastics on this group. Consequently, we urge to consider benthic foraminifera in plastic pollution studies *via* a tentative roadmap that includes (i) the use of their biological, physiological and behavioral responses that may unveil the effects of microplastics and nanoplastics and (ii) the evaluation of the indicative value of foraminiferal species to serve as proxies for the degree of pollution. This appears particularly timely in the context of the development of management strategies to restore coastal ecosystems.

## Introduction

Plastic pollution in marine environments has been reported as early as 1970 (Carpenter and Smith Jr 1972) with an increasing interest until the mid-1980s (Bean 1987). It nevertheless took nearly two additional decades to fully acknowledge the extent of the related environmental issues (Thompson et al. 2004). Due to both the exponential increase in plastic production (i.e., from 1.5 Mt in 1950 to 368 Mt in 2019, PlasticsEurope 2020) and the mismanagement of plastic waste (one third of the plastic waste (32 million Mt) from 93% of the world's population was classified as mismanaged in 2010, Borrelle et al. 2020), the 5 to 13

Mt of plastics discharged into the ocean every year, are expected to reach to up to 90 Mt/year by 2030 under business-as-usual scenarios (Borrelle et al. 2020). As an inherently durable material, plastic debris persist in the environment and are dispersed over long distances by winds and water currents (Alimi et al. 2018). The potential threats related to plastic debris *via* ingestion or leaching of contaminants (additives and persistent organic pollutants, see review in Delaeter et al. 2022) have been identified as a major global conservation issue and a key priority for research (Vegter et al. 2014, Harrison and Hester 2019, Seuront et al. 2022).

Plastic debris typically constantly degrade and fragment into smaller and smaller pieces over time under UV radiation and wave actions to eventually form microplastics (<5 mm; MPs) and nanoplastics (<100 nm; NPs). These small particles continuously sink towards the seafloor where they are typically buried in unvegetated and vegetated sediments in subtidal and intertidal coastal areas (Cozzolino et al. 2020). Noticeably, coastal ecosystems like seagrass and macroalgal meadows (Cozzolino et al. 2020), mussel beds (Nicastro et al. 2022), coral reefs (Reichert et al. 2022), tidal marshes and mangroves act as barriers against the dispersal of MPs and NPs debris towards the marine environment (Martin et al. 2020). As such, coastal habitats are major sinks for MPs and NPs, which enter long-term sequestration in sediments (Martin et al. 2020). As a consequence, plastic pollution may interfere with the key role played by living organisms in coastal ecosystems in mitigating the effects of climate change by storing carbon dioxide (CO<sub>2</sub>) in sediments (Taillardat et al. 2018). Yet, the effects of plastic burial on the benthic biocoenosis of intertidal areas and coastal shallow-waters have been largely overlooked.

Of the studies that have explicitly tested the effects of plastic on benthic species, relatively few have attempted to consider MPs and NPs pollution and meiofaunal species which, for the most part, are invisible to the naked eye, but are nevertheless crucial elements of coastal benthic ecosystems (Schratzberger and Ingels 2018). In particular, meiobenthic foraminifera

72 are an important component of these coastal ecosystems. Amongst meiobenthic organisms  
73 (<1 mm), benthic foraminifera (Rhizaria) may represent up to 50% of the benthic eukaryotic  
74 biomass in coastal sediments (Moodley et al. 2000). They also contribute significantly to the  
75 carbon and nitrogen biogeochemical cycles in coastal ecosystems (Jauffrais et al. 2019,  
76 Choquel et al. 2021). They occupy a major trophic position through bacterivory, herbivory or  
77 carnivory (Nomaki et al. 2008, Chronopoulou et al. 2019). They also actively participate in  
78 the benthic ecosystem functioning *via* sediment mixing and bioirrigation, hence enhancing the  
79 fluxes of particulate and dissolved elements at the sediment-water interface (Bouchet and  
80 Seuront 2020, Deldicq et al. 2020, Deldicq et al. 2021a). In addition, foraminifera can  
81 accumulate large quantities of nitrate in their cell and reduce it through denitrification under  
82 low-oxygen conditions (Risgaard-Petersen et al. 2006, Piña-Ochoa et al. 2010, Choquel et al.  
83 2021); their contribution to the nitrogen cycle being, for instance, up to 70% in the North Sea  
84 (Piña-Ochoa et al. 2010) or ranging from 50% to 100% in Swedish fjords (Choquel et al.  
85 2021). In the context of biomonitoring, benthic foraminifera have been shown to be good  
86 sentinel of the health of benthic habitats (Armynot du Châtelet et al. 2004). Due to their  
87 sensitivity to environmental changes, shifts in species composition of benthic foraminiferal  
88 communities quickly reflect changes in environmental conditions (Schönfeld et al. 2012).  
89 Hence, they are used as indicators of pollution (e.g. Alve 1995, Francescangeli et al. 2016,  
90 Polovodova Asteman et al. 2015), such as oil spills (e.g. Morvan et al. 2004), drill cutting  
91 (e.g. Mojtahid et al. 2006), element trace metals (e.g. Armynot du Châtelet et al. 2004), urban  
92 sewage (e.g. Melis et al. 2019), and aquaculture (e.g. He et al. 2019). They are also considered  
93 as accurate bioassay in ecotoxicological experiments which reported test (shell)  
94 malformations (Le Cadre and Debenay 2006), alteration of the growth (Denoyelle et al.  
95 2012), oxydative stress (Frontalini et al. 2018a), physiological changes (Losada Ros et al.  
96 2020), proteom modifications (Ciacci et al. 2022) and changes in species composition of

foraminiferal communities in mesocosm (Frontalini et al. 2018b) in response to, respectively, copper, oil-based drilling muds, element trace metals, cadmium and mercury exposure.

Because of the recognized fundamental role of foraminifera in the coastal benthic realm (Moodley et al. 1998, LeKieffre et al. 2018), it is an important concern how MPs and NPs can affect them. Specifically, plastic burial in benthic sediments may lead to the ingestion of MPs or NPs and to long-term exposure of benthic foraminifera to a variety of additives and chemicals leaching from plastic items in the sediment. Element trace metals, for instance, which may accumulate onto and then leach from weathered plastic surface, are known to be harmful for foraminifera (e.g. Le Cadre and Debenay 2006, Frontalini et al. 2018a, 2018b). Noticeably, a wide range of physiological and ultrastructural impairments (e.g., involving thickening of organic lining of test, mitochondrial degeneration, proliferation of degradation vacuoles, lysosomes, residual bodies and the increased production of neutral lipids and of reactive oxygen species) have been reported in benthic foraminifera exposed to element trace metals (Frontalini et al. 2018a), as well as morphological abnormalities and decreased growth rate (Le Cadre and Debenay 2006, Denoyelle et al. 2012). In addition, sediment anoxia induced by plastic accumulation in the marine litter (Krause et al. 2020) may also contribute to shape benthic foraminifera communities and promote low-oxygen-tolerant species. On the basis of the above evidences, it seems legitimate to hypothesize that benthic foraminifera would be highly affected by plastic pollution.

In this context, through a systematic review, this study quantifies the current state of plastic pollution research on benthic foraminifera, presents key results, and summarizes perspectives that warrant further study. Here, we highlight why foraminifera should be given more emphasis in studies aiming to understand the effect of plastics on the benthic biocoenosis of intertidal areas and coastal shallow-waters. We further suggest a way forward toward consolidating research and policy efforts to better address the effect of plastic

pollution as a potential driver of benthic foraminiferal community structure and role in the functioning of such key habitats.

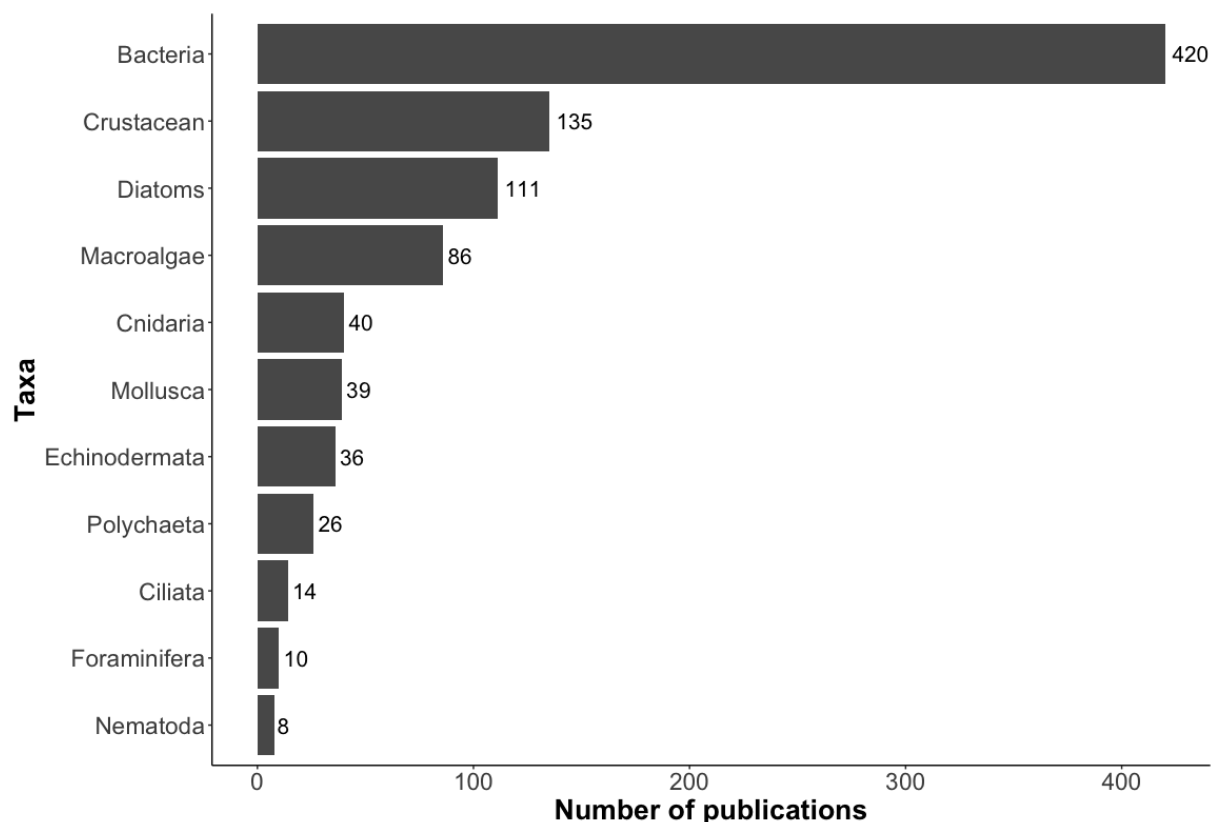
## **Methods**

The field of research dedicated to plastic pollution in benthic marine ecosystems is currently one of the most prolific. A literature search was performed in the Web of Science (last accessed on January, 13, 2023) using the words plastic (i.e. 'plastic\*'), marine (i.e. 'marine') and benthic (i.e. 'benth\*'). A total of 928 publications were returned. To evaluate the research effort for the main taxa encountered in benthic coastal habitats, the literature search was refined through the use of different combinations of keywords (i.e. 'bacteria\*', 'crustacean\*', 'diatoms\*', 'macroalgae\*', 'cnidaria\*', 'mollusca\*', 'echinodermata\*', 'polychaeta', 'ciliata\*', 'nematoda\*', 'foraminifera', respectively, together with 'plastic\*', 'marine' and/or 'intertidal' and/or 'coastal', and 'benth\*'). The reference lists within these studies were also scrutinized to identify additional relevant studies. For this opinion paper, we only included English-written studies that assessed the impact of plastic pollution on the above-mentioned taxa. A total of 925 studies were selected. This literature search allowed us to evaluate the status of the research on benthic foraminifera and plastic pollution compared to other biological components of benthic ecosystems.

### **Plastic pollution and benthic foraminifera: the big void**

Among the studies that considered the effect of plastic pollution on marine organisms, a vast majority (*i.e.*, 81%) essentially targeted bacteria, algae and crustaceans (Fig. 1). Protists were critically underrepresented (*i.e.*, 2%) and amongst the 24 papers that considered them, ten of these studies focused on benthic foraminifera; amongst which four observed benthic

foraminifera on floating and benthic plastic debris (Jorissen 2014, Finger 2017, Birarda et al. 2021, Subías-Barata et al. 2022), four focused on the inclusion of plastic particles in foraminiferal tests (Tsuchiya and Nomaki 2019, Birarda et al. 2021, Joppien et al. 2022a, Romano et al. 2023) and only four *stricto sensu* monitored the effect of MPs or NPs (Ciacci et al. 2019, Langlet et al. 2020, Birarda et al. 2021, Joppien et al. 2022b). A recent review (Delaeter et al. 2022) showed that, in plastic leachates-related studies, only 0.64% studies considered benthic foraminifera, while about 98% were on macro-invertebrates. Note that, according to our literature survey, there is still no study considering the impact of plastic pollution on planktic foraminifera. In short, regardless of coastal ecosystems, the assessment of MPs and NPs impacts on foraminifera overwhelmingly lags behind other marine species.



**Figure 1.** Research effort (number of publications) considering the physical and toxic effects of plastic pollution for the most relevant marine benthic taxa.



161

162 Drifting and benthic plastic debris may be colonized by benthic foraminifera (Jorissen  
163 2014, Finger 2017, Birarda et al. 2021, Subías-Barata et al. 2022). This may contribute to the  
164 dispersion of benthic foraminifera, and their introduction outside their natural range as  
165 observed on rafted plastic items with shallow-water foraminiferal fouling transported by  
166 currents from Japan to Hawaii and North-America (Finger 2017).

167 Foraminifera have mainly four types of tests: those that assemble calcium carbonate crystals  
168 constructed intracellularly and build tests (porcelaneous test), those that crystallized calcium  
169 carbonate (mainly) extracellularly (hyaline), those that collect sediment particle in the habitat  
170 for a test (agglutinated), and those with an organic membrane. Plastic particles were found to  
171 be included in the test of hyaline (Joppien et al. 2022a) and agglutinated foraminifera  
172 (Tsuchiya and Nomaki 2019, Birarda et al. 2021, Romano et al. 2023), and, as such, might  
173 further be transferred to predators of foraminifera like gastropods, copepods, polychaetes,  
174 decapods, polychaetes and fishes (Buzas and Carle 1979, Culver and Lipps 2003, Nomaki et  
175 al. 2008). Inclusion of plastic particles into the test of benthic foraminifera may likely expose  
176 them to the harmful effects of plastic additives; see Delaeter et al. (2022) for a specific review  
177 on the impacts of plastic leachates on organisms.

178 Amongst the only four papers dealing with the *stricto sensu* influence of plastic on benthic  
179 foraminifera (see details in Table 1), three dealt with the effect of particles (Ciacci et al. 2019,  
180 Birarda et al. 2021, Joppien et al. 2022b) and two with the effects of additives (Langlet et al.  
181 2020, Birarda et al. 2021). Noticeably, the exposition and ingestion of NPs of polystyrene (1  
182 mg.L<sup>-1</sup>) induced physiological stress by promoting the accumulation of neutral lipids and  
183 enhanced reactive oxygen species production in *Ammonia parkinsoniana* (Ciacci et al. 2019).  
184 In the presence of seawater-soaked polyethylene MPs (1 particle.mL<sup>-1</sup>), the coral-reef species  
185 *Amphistegina gibbosa* indifferently fed on MPs and on *Artemia* sp. nauplii (Joppien et al.

2022b). The heterotrophic behavior of this symbiont-bearing species was clearly altered; hence, it had to be more reliant on autotrophy. Furthermore, *Rosalina bradyi*, *Textularia bocki*, and *Lobatula lobatula* were found to colonize *in situ* a plastic bag (most likely polyethylene) buried in the sediment (Birarda et al. 2021). The accumulation of protein beta-sheets was observed in all three species, a typical feature observed during oxidative stress cytotoxicity (Novak et al. 2019). The authors hypothesized that the accumulation of MPs debris and additives both in the cytoplasm and agglutinated test (i.e., *T. bocki*) may alter the biomineralization process in foraminifera. Laboratory experiments further showed that the plastic additive bis-(2-ethylhexyl) phthalate ( $0.3 \text{ mg.L}^{-1}$ ) can be incorporated in the cytoplasm of *R. globularis* (Birarda et al. 2021). However, the intertidal foraminifera *Haynesina germanica* did not show any change in motion behavior nor in respiration rate when exposed to leachates from virgin polypropylene pellets (20 and 200 mg of pellets. $\text{L}^{-1}$ ; Langlet et al. 2020).

These limited number of studies have partially explored the potential hazard of plastic contamination of foraminifera in suggesting that MPs and NPs may interfere in the feeding behavior of benthic foraminifera and generate physiological stress. However, they do not allow to draw any robust conclusion, in particular because of the heterogeneity between studies in terms of targeted foraminiferal species, type of plastic polymer, sizes and concentrations of plastic particles, exposure time and measured parameters (Table 1), which altogether further hampers any comparison among these works. Hence, we emphasize that our knowledge is entirely insufficient for an integrated understanding of MPs and NPs effects on foraminifera, as evidenced by the fact that the response is apparently dependent on the type of plastic and foraminiferal species.

Given the ubiquity and extent of plastic pollution, the ever-growing number of studies assessing the effect of plastics on a wide range of organisms and the aforementioned potential

211 ecological role of benthic foraminifera in key coastal habitats, it is striking that they have  
212 been disregarded for so long, which further stresses the need to amend the *status quo*. The  
213 lack of attention to a group as dominant in coastal sediments as foraminifera has received  
214 from the scientific community is no longer justified neither on methodological nor ecological  
215 grounds.

Table 1: Publications on the effects of plastic on benthic foraminifera: studied species, plastic types and methodological approaches.

Study	Species	Symbiont/ Chloroplast	Habitat	Type of study	Polymer/Additives	Particles size	Exposure	Concentration	Time of the exposure	Parameters
Birarda et al. 2021	<i>Rosalina globularis</i>	None	Temperate, Coastal, shallow-water	Experimental	Phthalate (DEHP)	/	Additive	0.3 mg.L <sup>-1</sup>	7 weeks	Oxydative stress
	<i>Rosalina bradyi</i> , <i>Textularia bocki</i> , <i>Cibicidoides lobatulus</i>	None	Temperate, Coastal, shallow-water	<i>In situ</i>	Polyethylene	Plastic bag	Particles and additive	/	/	Particle inclusion in the test, Oxydative stress
Ciacchi et al. 2019	<i>Ammonia parkinsoniana</i>	None	Temperate, Coastal, shallow-water	Experimental	Polystyrene	42 nm	Particles	1 mg.L <sup>-1</sup>	24h	Ultrastructural and physiological changes (oxydative stress)
Joppien et al. 2022b	<i>Amphistegina gibbosa</i>	Symbiont-bearing	Tropical, Coral reefs, shallow-water	Experimental	Polyethylene terephthalate	150-300 µm	Particles	1 and 2 particles.mL <sup>-1</sup>	24h	Feeding behavior ( <i>Artemia</i> sp. versus plastic particles)
Langlet et al. 2020	<i>Haynesina germanica</i>	Kleptoplastic	Temperate, Coastal, Intertidal	Experimental	Polypropylene	3.3-4.7 mm	Leachates (24h in seawater)	20 and 200 mL of pellets.L <sup>-1</sup>	10h	Motion behavior, Respiration

## **Benthic foraminifera: culprits and victims of plastic pollution?**

It is generally recognized that MPs and NPs have a negative impact on organisms (e.g. Delaeter et al. 2022), but this is not confirmed to be true for foraminifera. Ironically, benthic foraminifera may not be only prime suspects but also guilty of sequestering both MPs and NPs in sediment through their bioturbation activity that would actively transfer plastic particles from the water-sediment interface to the sediment matrix. Noticeably, they are able to burrow particles in the size range (10-125  $\mu\text{m}$ ) of MPs (Gross 2002). This may help to isolate plastic particles from biologically active area (surface sediments) to less active area, and promote fossilization of MPs and NPs. However, sub-sediments may also constitute a reservoir where plastics are trapped and be further re-introduced in the food-web by benthic organisms feeding in this compartment (Sandgaard et al. 2023). In addition, the inclusion of plastic particles in the test of hyaline and agglutinated benthic foraminifera (Tsuchiya and Nomaki 2019, Birarda et al. 2021, Joppien et al. 2022a, Romano et al. 2023) possibly contributes to the transfer of plastic particles and additives through the food web, and to the trapping of MPs and NPs in the sediment. In this specific context, benthic foraminifera became their own victims as the burial of MPs and NPs is likely to expose them to ever increasing concentrations of the countless additives and chemicals carried by plastic items. We do not yet have evidence of whether they are culprits or victims, but at the very least, benthic foraminifera that take up plastic provide an archive for the accumulation of MPs and NPs in marine habitats, and this is *in fine* likely to provide additional evidence of how plastic can be considered as a key stratigraphic indicator of the Anthropocene as a distinctive strata component (Corcoran et al. 2015, Zalasiewicz et al. 2016, Dibley 2018). We hence advocate for more comprehensive research programs (*i*) to understand the role of benthic foraminifera

in plastic trapping in sediments, and (ii) to improve our poor knowledge of the effect of plastic particles and their leachates on benthic foraminifera.

The assessment of the pernicious non-lethal effects of MPs and NPs on organisms is a challenge in the benthic coastal realm, particularly in minute organisms like benthic foraminifera that represent an emerging model in coastal ecosystems. Despite their noticeable small number relative to the available literature (see Fig. 1), the recent studies on the response of benthic foraminifera to various aspects of plastic exposure (Ciacci et al. 2019, Langlet et al. 2020, Birarda et al. 2021, Joppien et al. 2022b) have stressed how critical it is to understand why, how and under which environmental conditions MPs and NPs affect benthic foraminifera, and we plea to address the following scientific questions (Fig. 2):

(1) What are the processes involved in the integration of plastic particles in foraminiferal test? In particular, is this particle size- and/or concentration-dependent? Does this occur during shell construction that includes calcification and agglutination or *via* ingestion? Does this enhance the exposure of benthic foraminifera to plastic?

(2) Does sediment reworking by benthic foraminifera contribute to MPs and NPs accumulation in coastal sediments?

(3) What are the potential harmful effects of plastic on benthic foraminifera at community level, individual level, and cellular level?

(4) *In fine*, do the harmful effects of MPs and NPs alter the role of foraminifera in the benthic ecosystem functioning?

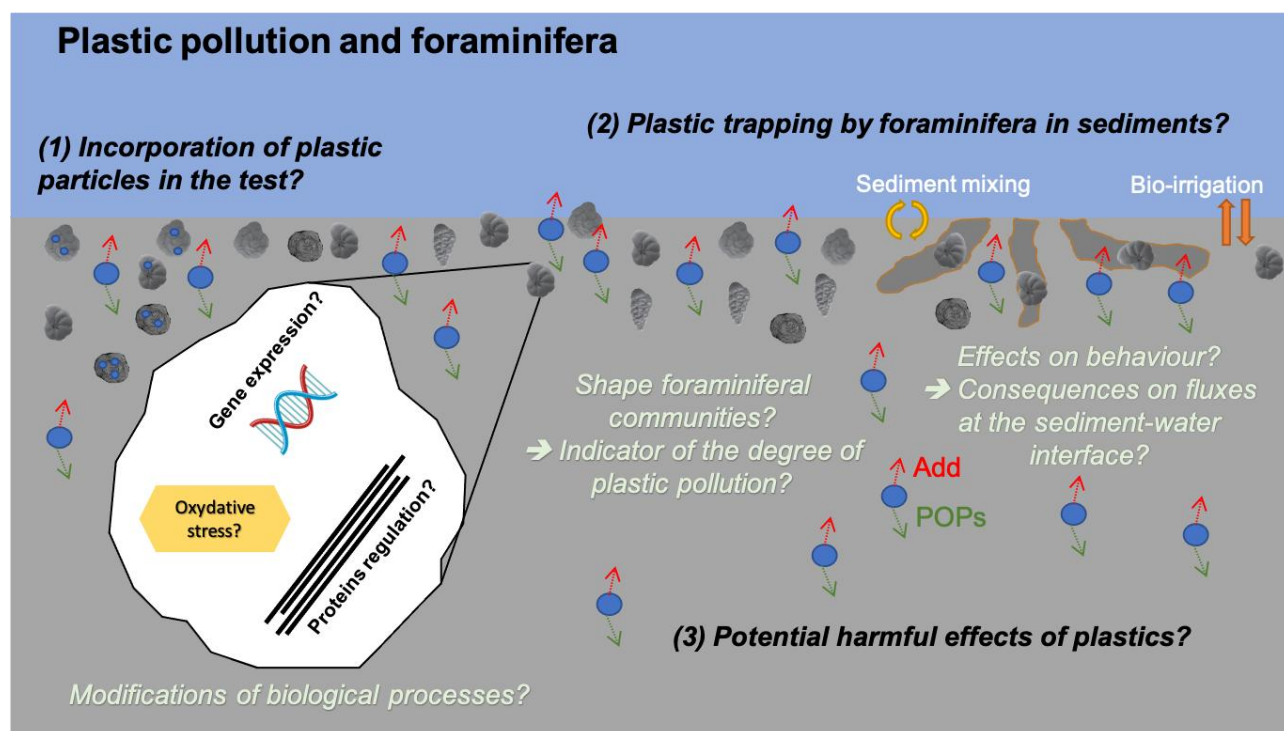


Figure 2. Schematic of the questions to be tackled to understand (1) how much plastic particles are incorporated in foraminiferal test, (2) to what extent foraminifera may contribute to the trapping of MPs and NPs in coastal sediments and (3) the potential harmful effect of plastic on (a) species composition of foraminiferal communities (community level), (b) behavior (individual level), (c) cellular alterations and physiological changes (cellular level), and (4) the possible consequences on the benthic ecosystem functioning *i.e.* sediment mixing and bioirrigation. These questions are intended to shed light on the emerging opportunities of benthic foraminifera as proxies for the characterization of plastic pollution in coastal ecosystems. (Filled blue circles: MPs/NPs particles, Add: additives, POPs: persistent organic pollutants)

Addressing those questions can be achieved in future researches that should—and ideally concurrently—monitor the hazards of MPs and NPs exposure at different levels from cells to communities in the following roadmap:

(i) Cellular level: Underlying mechanisms behind the responses observed at the individual level can be understood through the study of cellular alterations and physiological changes. For instance, recent advances in omics technologies have provided new tools to understand the effects of contaminants, which, in turn, may serve as biomarkers to be used in environmental monitoring as early warning of pollution (Tomanek 2011; Ciacci et al. 2022). In details, the response of benthic foraminifera to MPs and NPs particles and leachates are now deeply accessible through the advance in transcriptomics (Titelboim et al. 2020), proteomics (Stuhr et al. 2018) and microscopy (Frontalini et al. 2019). In addition, alterations in the proteome can, for instance, have consequences on the fitness (i.e. reproductive success) of an organism.

(ii) Individual level: While pernicious non-lethal effects of MPs and NPs may likely not be easy to observe in communities, targeted experiments on foraminiferal individuals with environmentally relevant concentrations and focusing on specific biological features known to respond to contamination can address such limitations. Specifically, motion behavior is an acknowledged keystone process behind the success of foraging, mate-finding and habitat selection (Bowler and Benton 2005). Motion behavior is still, however, the forgotten child of foraminiferal ecology, despite its increasingly recognized variability (Seuront and Bouchet 2015, Jauffrais et al. 2016) and role in bioturbation (Bouchet and Seuront 2020, Deldicq et al. 2020, Deldicq et al. 2021a). In addition, benthic foraminiferal behavior is affected in the presence of a stressor (gravity, organic matter, temperature; Seuront and Bouchet 2015, Jauffrais et al. 2016, Deldicq et al. 2021b) that may have further consequences on their search for food and for the optimal microhabitat. In this context, investigating the behavioral changes induced by MPs and NPs on benthic foraminifera will contribute to improve our understanding of the effects of plastic pollution on their survival, may serve to predict population-level effects.



We further stress that measurements suggested at points *i)* and *ii)* does not require long-term incubation and recent studies confirmed they can be easily performed on foraminifera, which may facilitate their implementation.

*iii)* Community level: MPs and NPs may implicitly alter the quality of habitats inhabited by benthic foraminifera, hence undermine the survival of some species, and ultimately constrain the composition of foraminiferal communities. To reveal the response of community composition to MPs and NPs, it is essential to monitor their spatial distribution through joint *in situ* sampling surveys of MPs, NPs, and foraminiferal species. By applying spatial models, *i.e.*, spatial varying coefficient model (Murakami et al. 2017, Matsuba et al. 2020), to these spatial data, it may be possible to predict the distribution and composition of foraminiferal communities in response to spatial patterns of MPs and NPs and their concentrations in sediments, as well as ocean environmental factors (e.g. current velocity) that affect the distribution of MPs and NPs. Such a modeling approach would be one way to determine how MPs and NPs pollution, coupled with macro-environmental changes in the ocean, including climate change, could affect foraminiferal communities. In addition, taking advantage of the recent development of the use of benthic foraminifera to assess ecological quality statuses (Alve et al. 2016, Bouchet et al. 2021, Parent et al. 2021), it may provide an opportunity to develop an index of the degree of plastic pollution in coastal ecosystems sediment through the identification of indicator species of the presence/absence of MPs and NPs. Finally, a better understanding of benthic foraminiferal community response to plastic pollution will eventually help to grasp their role in marine ecosystems functioning.

## **Conclusion**

Benthic foraminifera offer a putatively endless sets of opportunities to tackle the question of the potential harmful effects of plastic pollution, from the cellular to the community level. We plea here to embrace the opportunity to see in these abundant but minute—though highly

neglected (see Fig. 1)—organisms a unique prospect to refine our understanding of the effects of one of the main environmental threats of the “Anthropocene” on the structure and functions at play behind the future of coastal ecosystems under climate change. *In fine*, foraminifera will provide proxies of the history and the degree of plastic pollution on the benthic ecosystem. Last but not the least, there is, to date, no study on the interaction between plastic and planktic foraminifera, although they may be in contact with MPs and NPs in the water column. This last aspect must also deserve more attention in the future.

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### **Author Contributions**

L.S., H.N. and V.M.P.B conceived the idea of the paper. L.S. and V.M.P.B. wrote the original draft. The manuscript was written through contributions of all authors. All authors have given approval to the final version of the manuscript.

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### **Competing interests statement**

The authors have no competing interests to declare.

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