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Macroecotoxicology: challenges and opportunities to study broad-scale biodiversity patterns under the effect of microplastics contamination

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Abstract

Despite several advances in the field of ecotoxicology, the implication of the effects of xenobiotics on species' macroecological responses can only be inferred. Almost a decade ago Beketov & Liess (2012)[1] called for the integration of the fields of ecotoxicology and macroecology as a way to unravel the global impacts of environmental pollution on biodiversity patterns. In this mini-review, we dig into the literature from the last three years on the responses of marine invertebrates to microplastics (MPs) as a study case to assess the challenges and opportunities for the emergingfield of macroecotoxicology. We discuss 1) to what extent the recent studies on the marine invertebrate species responses to MPs have applied the principles of macroecotoxicology and 2) how macroecotoxicology can be used to evaluate the shifts in expected species diversity patterns, and so to define priorities for investigating global effects of MPs on marine invertebrate species.

Keywords: ecotoxicology, environmental gradients, macroecology, species interactions, traits

Introduction

In the Anthropocene, environmental pollution directly and significantly threatens biodiversity, affecting cellular to community levels. Among the existent pollutants, microplastics (MPs, < 5 mm) are ubiquitous to all ecosystems at high concentrations [2,3], and their ingestion and accumulation affect species' ecological functions [4–6]. The available information about MPs has skyrocketed in the past decades, and the knowledge of species responses to their effects has also increased [7,8]. Ecotoxicology has provided scientific information through studies of xenobiotics' fate and adverse effects. Current ecotoxicological methods are mainly based on assessing toxicity measured by biomarkers, which are measurable effects of contaminants on individuals, populations, and communities, applied in the field and the laboratory [9]. The broad ecotoxicology field can also evaluate the potential effects of MPs at ecosystem levels, but in a more complex and often challenging way [10]. On one hand, a bottom-up approach (sensu [1]), which uses individual effects to reach conclusions about ecosystem effects, may fail to find common patterns across spatial and temporal scales. On the other hand, comprehensive patterns resulting from individual responses can become relevant to ecosystem management and conservation [11].

Species' responses to environmental contamination tend to be complex due to the effects of multiple stressors and intra- and interspecific interactions among species [12]. Therefore, understanding the effect of contaminants on overall biodiversity patterns, such as spatial gradients in taxonomic richness, functional traits, and phylogenetic diversity, requires investigating the variability in species' responses to stressors over large geographical and temporal scales under a cross-taxonomic comparative approach. Such approach is the basis of macroecology, which is devoted to studying ecological systems' emergent statistical regularities (i.e., patterns), mainly regarding species diversity, abundance, and geographic distribution [13]. The most common aspect of macroecology is using large ecological datasets, statistical methods, and biodiversity theory to study spatial and temporal patterns governing the diversity and distribution of species from regional to global scales [14]. The overarching goal of macroecology is to derive general principles underlying the structure and function of ecological systems [15–17]. Thus, applying a macroecological approach to ecotoxicology can help describe and explain how contaminants systemically affect species diversity and distribution patterns. The search for emerging patterns of the responses of various species to contamination would represent the "top-down" approach to ecotoxicology previously suggested by [1]. Because contamination is one of the main drivers of species distribution patterns in the Anthropocene, and extensive data are available on contamination, several research opportunities exist to integrate ecotoxicology with macroecology to reach conclusions on a macro-scale. Indeed, the time is ripe for *macroecotoxicology* [1,18] to help answer the central questions of ecotoxicology.

Traditional macroecological patterns include: 1) spatial patterns of diversity (e.g., latitudinal diversity gradient), 2) frequency distributions of ecological traits (e.g., geographic range size, abundance, body size), 3) spatial (and temporal) variation of ecological traits (i.e., ecogeographical rules [Marquet, 2009]), and, more recently, 4) geographic and environmental variation (dynamics) of species interactions [20]. A similar endeavor in describing and explaining macroecotoxicological patterns can bring us closer to mitigating or even preventing the effects of contaminants by identifying common patterns across species that can inform us about the overall impact of pollutants on biodiversity (Figure 1). So far, however, ecotoxicological assessments still need to be made available for most species to derive macroecotoxicological patterns.

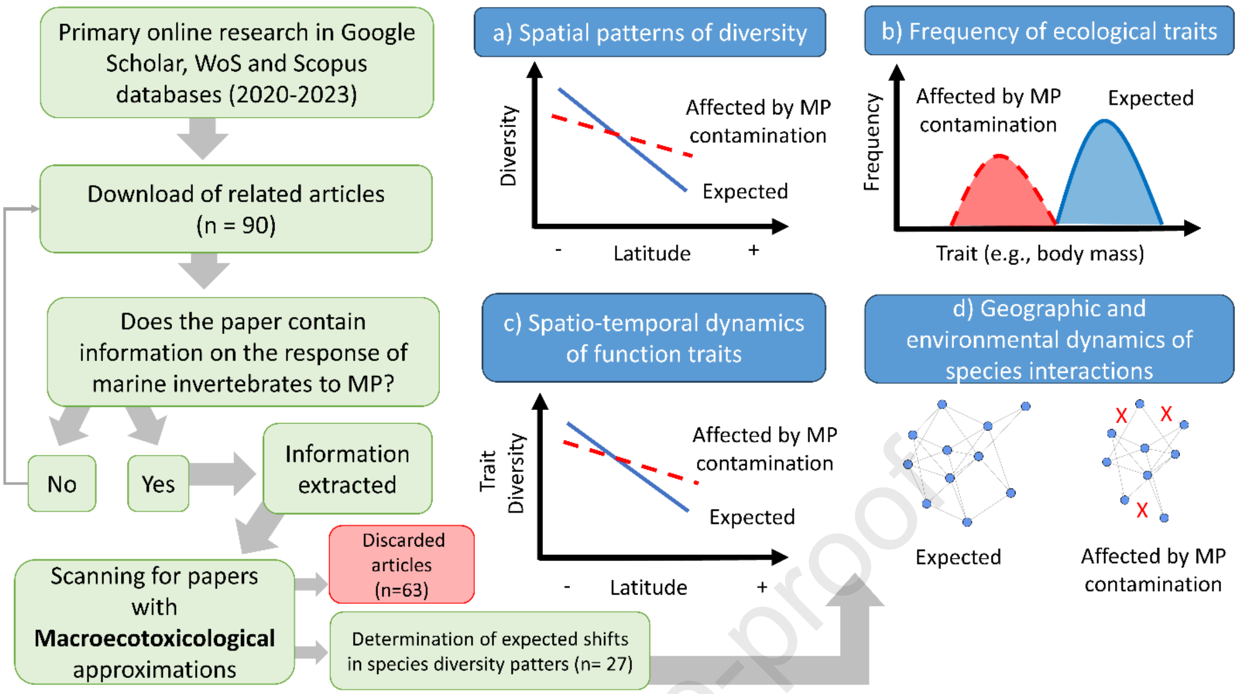

Figure 1. Flowchart diagram employed to obtain the literature used in this mini-review. The upper plots (a, b, c and d) illustrate how diversity (taxonomic, functional [traits] or interactions [represented in networks]) affected by MPs contamination could potentially deviate from the expected macroecological patterns. In species networks, the red X marks indicate the break of links between species, while the missing nodes (blue dots) represent the loss of species in a network.

In this mini-review, we used as a study case the recent literature on the ecotoxicological responses of marine invertebrates (90 studies retrieved from Google Scholar, Web of Science and Scopus databases from 2020 to 2023; Figure 1, Supplementaty Material) to identify patterns that emerge from individual studies, and that could be used for macroecotoxicological approximations. The search strings were ("plastic*" OR "microplastic*" OR "micro plastic*" OR "microplastic*" OR "MP") AND ("inverbrates*") AND ("marine*" OR "estuarine*" OR "beach*") AND ("effects" OR "responses"). We chose marine invertebrates because these are a sentinel group of species to study MPs [21], highly vulnerable to anthropogenic stressors [6], because MPs bioaccumulation can lead to negative impacts on their multiple bio-ecological processes [18,22,23,24] and due to the large number of studies reported on the presence and effects of MPs. Moreover, they play a crucial role in historical toxicological studies because of their wide range of tolerances to environmental stress, feeding type, and life strategies. Based on our mini-review, we also discussed the opportunities and challenges of deriving macroecotoxicological patterns from existing data.

Spatial patterns of diversity

These are amongst the most studied patterns in macroecology. The classic emerging pattern is the Latitudinal Diversity Gradient (LDG), describing an increase in species richness from the temperate (higher latitudes) to the tropical regions (lower latitudes) for most taxa studied so far [25,26]. A similar pattern emerges along elevational gradients, with species richness increasing towards lower elevations. Still, other patterns also emerge along elevation, such as peaks at mid-elevations and low-elevation plateaus [27]. Several mechanisms have been proposed to explain these patterns, from ecological to evolutionary ones, including climatic (e.g., temperature) controls on species' distributions and richness, with more species existing in favorable (e.g. warm and humid) conditions [28].

It has been shown that contamination may exert a similar effect to temperature and other climatic conditions in constraining species distributions [29] and, thus, perhaps, in determining local species richness. However, determining how much of the species diversity gradient might be affected by MPs pollution is complex [30,31] because species responses to pollutants can be context-dependent [32], and related to their metabolic variation across latitudes. As many contaminants are more bioavailable at lower latitudes, where more species richness and diversity exist, this could potentially lead to more species being affected by contamination [18].

Opportunities in macroecotoxicology for the study of marine invertebrates can come from the use of the ecotoxicological information showing how MPs contamination affect species responses (e.g., dispersal, migration, and establishment) that would alter the LDG, both due to the toxicity as well as to physical vectors and whether local extinction/colonization patterns could be associated with this and or with a combination of several contaminants. Our review identified studies indicating that the development and motility of marine invertebrates at the larval stages (which will determine the possibilities of dispersion and colonization of habitats) can be negatively affected by MPs pollution [33,34]; that MPs and plastics contamination reduce the local richness of macro and micro invertebrates on an intertidal shore and of benthic communities in mesocosms conditions [35]; and that MPs lowered metabolic levels [24,36], affecting species capacities to reproduce [24] and feed [37]. Accordingly, there is ample evidence that contamination is a mechanism that affects species diversity and thus potentially its latitudinal gradient, but no study has investigated this potential effect on LDG to date. Based on this evidence, our expectation is that the potential reduction of marine invetebrate species richness via local extirpation would be higher at low latitudes resulting in a shallower LDG with lower differences between the diversity of tropical and temperate regions (Figure 1a). Still, supporting data is necessary to verify how the latitudinal diversity gradient would actually be affected by increasing pollution.

Frequency of ecological traits

The patterns in the frequency of species traits across ecosystems indicate community structure. Some studies have pointed out that the frequency distribution of ecological traits has changed (e.g., flattening the distribution of body sizes given the extinction of large species) due to anthropogenic effects, such land use conversion [38–40]. Widespread contamination can potentially have the same effect as other anthropogenic factors, as it has been demonstrated to negatively affect animal traits, such as reducing body size [41,42].

Opportunities in macroecotoxicology include investigating how MPs contamination can be related to the frequency distribution of species functional traits within assemblages. Species traits related to MPs accumulation or physiological and biochemical effects can reveal the species' characteristics that would make them vulnerable to this contaminant [43]. Our review indicates that, in the case of crustaceans, smaller species, burrowers, swimmers, and omnivores tend to accumulate more MPs [18,22,44]. For benthic invertebrates, omnivores and deposit feeders were the most affected species [24], and their performance traits (e.g., mortality and reproduction) were as affected as the functional traits (e.g., feeding and behavior) [5]. Moreover, a reduction in body size of lobster species due to MPs exposure has been reported [45]. Based on these evidences, our expectation is that the frequency of species traits of an assemblage exposed to MPs contamination may shift from the expected under natural conditions. Specifically, a reduction in the trait frequency should be observed in polluted areas (Figure 1b), altough the magnitude of such frequency change requires supporting data to be tested.

Temporal and spatial dynamics of functional traits

Functional traits can vary in space and time, exhibiting macroecological patterns such as ecogeographic rules. These rules include geographic patterns such as increasing species' body sizes towards low-temperature environments (usually high latitudes) and range sizes towards high latitudes, known as Bergmann's and Rapoport's rules, respectively [46]. Recently, it has been shown that human pressures might help to predict current geographic range sizes [47] and that the high degree of human modification of natural ecosystems has primarily impacted the species-environment relationship [39] For instance, the mammalian body mass is lower closer to human settlements or in recently converted agricultural areas. Hence, it is likely that temporal and spatial dynamics of functional traits are also being affected by contamination [48,49].

Opportunities in macroecotoxicology include investigating how MPs contamination may affect species traits (e.g., body size) at both temporal and spatial scales. For other aquatic taxonomic groups such as fishes, MPs effects have been associated with an overall decrease in growth and body size [50]. Still, to date, such information is not yet available for marine invertebrates. Nevertheless, invertebrates may suffer a reduction in energy budgets when affected by MPs [37], which could lead to negative changes in the frequency of common traits related to growth, reproduction and dispersal.Consequently, trait diversity in polluted areas should differ from more pristine areas. Therefore, knowing or analyzing how pollution affects macroecological ecogeographic rules is an opportunity for studies in macroecotoxicology. Specifically, along latitutinal gradients, we esperculate that trait diversity will decrease when compared to the expected pattern if marine invertebrate species' responses to MPs contamination is taken into account (Figure 1c).

Geographic and environmental dynamics of species interactions

Species interactions within ecological networks (e.g., food webs) maintain ecosystem structure and functionality [51]. By being incorporated into the food webs, MPs may cause disruption of ecological interactions and thus network structure, as they alter species-prey relationships by inhibiting prey vigilance behavior [52,53] and species feeding behavior [54]. Indeed, our mini-review shows that it is already known that species of all trophic levels accumulate MPs in food webs with the presence of marine invertebrates [55,56]. MPs are vectors of other contaminants adhered to the particles' surface and can pass through the food chain [57]. Still, the effect of MPs on ecological networks depends on the capacity of the different trophic levels to depurate the particles [58]. Opportunities in macroecotoxicology include investigating how MPs might be disrupting ecological networks from regional to global geographical scales. Giving the reported alteration in species interactions due to MPs pollution, we especulate that MPs may lead to network disruption by the removal of nodes (i.e. species) or the links (i.e. the interaction between two species) (Figure 1d). Supporting data on observational macroinvertebrates interaction networks across large geographical areas would help to evaluate their ecological status.

Challenges and future perspectives

Using macroecological approaches with the available ecotoxicological data, global emergent patterns on species-responses to anthropogenic impacts can be identified and investigated. However, there are challenges in integrating both disciplines, whose purpose is to detect processes and large-scale biological patterns crucial for effective conservation and management actions under the continuous increase in MPs contamination or any other class of contaminants. Practically, methodological differences in assessing contaminants may lead to differences in their quantification and detection [4]. If quantifications were based on standardized ranges of MPs in species, then their effects would be comparable and thus would help to identify spatial patterns of MPs effect on traits in individual species, among species, and within assemblages. Moreover, the publication of standardized raw datasets of species-responses is not a common practice in Ecotoxicology [59]. Data sharing would increase the data available for compiling regional and continental scale assessments necessary to draw macroecotoxicological patterns, so researchers should be incentivized to publish primary data rather than just their results whenever possible. Datasets on marine invertebrate species-responses to MPs in the field are scarce, so significant knowledge gaps certainly exist and species macroecotoxicological patterns still need to be detected. As such, in this mini-review we could only speculate about how MPs pollution posibly shifts expected macroecological patterns of marine invertebrates, thus we acknowledge that supporting data is necessary to make evaluate such potential shifts on diversity patterns.

In this mini-review, we used marine and coastal invertebrates as a model system since they are an important sentinel group for detecting environmental changes. However, the framework proposed in this mini-review could be potentially tested in other species groups with other contaminants across geographical scales. By doing that, natural variation across sites (e.g. latitudes) can be exploited to understand how ecological processes are affected by pollutants [32], as to fulfill the knowledge gaps related to species diversity patterns in the Anthropocene. It is crucial to understand whether the effects seen at the species level represent general patterns that can be scaled up into global patterns. Scaling up these responses is necessary for regional assessments that could be further used as tools to help guiding conservation actions at mostly relevant scales. We believe that macroecotoxicology can aid in the detection of such patterns at global scales.

Conclusion

The prevalent effects of MPs contamination in basically all ecosystems makes it necessary to integrate the knowledge on species-contamination responses in a framework that seeks to understand how species diversity and distributions patterns are changing (as done by macroecology). After more than a decade since the call for the integration between ecotoxicology and macroecology by [1], we now make an urgent call for such integration by showing the opportunities of such an approach to advance our understanding of the effect of environmental pollution on biodiversity patterns. In turn, this could help derive additional predictions on such effects that could help mitigate them. Our literature search on the effects of MPs on marine invertebrates showed that studies had been largely dedicated to understanding focal species responses, mostly in laboratory exposure experiments. While the MPs effects are detected at the species level, the disruption of species performances could be changing global species diversity patterns. We propose that macroecotoxicology provides a roadmap for such global assessements.

Supplementary Material

List of the articles retrieved from the literature search.

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Declaration of interests

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

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