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A global perspective on microplastic bioaccumulation in marine organisms

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A B S T R A C T

Microplastic (MP) contamination of marine ecosystems has been confirmed as an environmental issue of global concern. A growing number of monitoring surveys has extensively documented the occurrence and distribution of a wide array of MPs of different sizes, shapes, colours, and polymeric compositions in seawater, sediments, and marine organisms worldwide. The presence of MPs in marine organisms has been explored in many species belonging to different taxonomic groups collected in diverse geographical locations. These studies have revealed the ingestion and the bioaccumulation of MPs in organisms at each trophic level, confirming the ubiquity of MP contamination in marine ecosystems. This systematic review aimed at summarizing the results of the vast literature concerning the bioaccumulation of MPs in marine organisms to 1) shed light on potential differences in MP body burden among different taxonomic groups and 2) investigate the spatial and temporal variation of MP bioaccumulation at the global level. Our analyses showed that, independently of the geographic origin of the sample, the MP body burden significantly differed among trophic levels and/or taxonomic groups. Zooplankton showed the lowest MP levels, while the highest levels were observed in vertebrates other than fish (i.e. mammals, birds and reptiles). In contrast, no temporal or geographical differences in MP bioaccumulation were noted, independently of the taxonomic groups. These results confirmed that all marine organisms can ingest and accumulate MPs, but the large variability in body burden within and among the taxonomic groups precludes the opportunity to identify global patterns of contamination.

1. Introduction

In the last decade, plastic pollution has emerged as one of the most worrisome environmental issues that our society has to tackle. The increased production and use of plastics, coupled with the mismanagement and disposal of single-use or unusable plastic waste at their end-life have resulted in widespread and massive contamination of marine, freshwater and terrestrial ecosystems (e.g., Li et al., 2020; Xu et al., 2020). Although plastic wastes 'populate' all habitats, including remote areas and glaciers (e.g., Ambrosini et al., 2019; Parolini et al., 2021; Rota et al., 2022), the attention on plastic contamination has predominantly focused on marine ecosystems. It has been estimated that ~10 million tons of plastics enter the oceans annually and that between 100 and 250 million tons of plastics will be present in the oceans in 2025 (Jambeck et al., 2015). In addition, several studies have estimated and compared the amount of plastic debris in different ocean locations and compartments (see Hale et al. 2020; Isobe and Iwasaki, 2022), suggesting that the mass of plastics can be at least one order of magnitude smaller than what was supposed to have leaked (Jambeck et al., 2015). Anyway, a large amount of plastic debris has continuously accumulated in the ocean over the past 60 years (Ostle et al., 2019), making marine plastic contamination irreversible and globally ubiquitous (Villarrubia-Gómez et al., 2018). A heterogeneous array of large-sized plastic items (i.e., macro- and mesoplastics, >25 mm and > 5 mm, respectively) with different shapes, colours, and polymeric compositions have been identified in marine ecosystems (Watt et al., 2021). Once in the environment, such plastic items can undergo breakage and degradation due to physical, chemical, and biological processes (Hartmann et al., 2019; Jambeck et al., 2015), generating small-sized plastic items, named microplastics (MPs) and nanoplastics (NPs). MPs have been recently categorized as any plastic item in the 1 to < 1,000 μm size range, while NPs as items in the 1 to < 1,000 nm size range (Hartmann et al., 2019). Whilst limited information is currently available concerning the presence of NPs in marine ecosystems because of the lack of quantitative analytical techniques for their isolation and identification (Gaylarde et al., 2021), MP contamination has been identified and confirmed as an environmental issue of global concern (Rochman and Hoellein, 2020). The occurrence and distribution of MPs have been extensively

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documented in seawater, marine sediments, and biota worldwide (Hale et al., 2020). Because of their persistence, MPs last for a long time in marine ecosystems, whereby they are distributed throughout the whole water column according to their buoyancy, which depends on the density of every single polymer. Moreover, the small size of MPs makes them prone to be ingested and accumulated by a wide range of marine organisms belonging to different taxonomic groups, trophic levels, and feeding strategies. Bioaccumulation (or body burden) of MPs occurs when their uptake from the environment by all possible routes – i.e., contact, ingestion, and/or respiration –, from any source – i.e., water, sediment, or prey – exceeds the ability of the organism to excrete them (Wang et al., 2016). This process was confirmed in zooplankton, bivalves, crustaceans, fish, reptiles, birds, and marine mammals (e.g., Guzzetti et al., 2018; Palmer and Herat, 2021; Pennati et al., 2022). Moreover, a recent systematic literature review of field and laboratory investigations performed on different marine species has examined the occurrence of bioaccumulation and biomagnification of MPs across a general marine food web, confirming that bioaccumulation occurs within each trophic level, while no clear evidence emerged for biomagnification (Miller et al., 2020). The bioaccumulation of MPs in marine organisms can result in potential health hazards because of physical (e.g., injuries due to mechanical interactions between MPs and tissues), chemical (e.g., toxicity caused by additives such as dyes, plasticizers, or contaminants adsorbed on MP surface), and biological (e.g., infections caused by pathogenic bacteria colonizing the MP surface) processes (Blackburn and Green, 2021; Danopoulos et al., 2020). However, despite the increasing number of field and laboratory studies that have assessed the ingestion, accumulation, and potential adverse effects of MPs in marine organisms, the implications of the MPs-organisms interactions remain unclear and often contrasting. Indeed, on one hand, a growing amount of evidence has shown that exposure to MPs of different shapes, sizes, and polymeric compositions can induce negative impacts at the sub-individual (e.g., alteration of metabolism, the onset of oxidative stress, neurotoxic, genotoxic and inflammatory effects; Prokić et al., 2019; Parolini et al., 2020) and individual levels (e.g., a decrease of growth rate and increase in malformations; Messinetti et al., 2018; Haegerbaeumer et al., 2019; Jeong and Choi, 2019; Palmer and Herat, 2021). On the other hand, other studies have reported neutral outcomes (e.g., Canniff and Hoang, 2018; Foley et al., 2018).

The risks related to MP contamination can be defined as the likelihood of the occurrence of adverse effects after the ingestion and/or accumulation (i.e., exposure) of MPs (GESAMP, 2020). Thus, the investigation of the MP body burden represents a crucial process in the environmental risk assessment of these emerging contaminants. Although several monitoring studies have consistently demonstrated that marine organisms efficiently ingest MPs, they have also reported high variability in bioaccumulation, depending on the taxonomic group and geographical origin of the samples (Miller et al., 2020; Prokić et al., 2021; Covernton et al., 2021). Given this large heterogeneity in the literature results, the present study aimed at 1) summarizing the current, published findings of MP bioaccumulation in marine organisms, 2) quantifying the possible differences in MP body burden related to taxonomic groups and identifying the putatively more suitable taxonomic groups for monitoring MP contamination, 3) examining the spatial and temporal variation in MP bioaccumulation at the global level.

2. Materials and methods

2.1. Data collection and selection

A systematic review of the global literature on MP contamination in individuals of diverse marine species belonging to different taxonomic groups of purely aquatic organisms (i.e., zooplankton, crustaceans, molluscs, fish) was performed according to an established protocol (Moher et al., 2009; Miller et al., 2020). An in-depth literature search was carried out to explore the bioaccumulation of MPs in marine ecological indicators belonging to different taxa and collected exclusively in the field at diverse geographical locations over a global scale. This search was performed in Google Scholar, Scopus, and Web of Science search engines. It was concluded in March 2022 and covered the range of years between 2010 and 2022. The following keywords were included in the search: microplastics, ingestion, bioaccumulation, marine organisms and FTIR (i.e., Fourier Transform Infrared Spectroscopy). Moreover, additional references were also extracted from the reference lists of the inspected papers, as well as from review studies. This systematic review of the literature identified 6,090 publications. After the removal of duplicate records, only publications focused on field studies in marine environments were considered. We thus excluded publications reporting results from studies on MP contamination in freshwater organisms, laboratory experiments to assess MP ingestion and/or bioaccumulation, studies on the toxicity of MPs towards marine species, setup of methods to isolate and to characterize MPs, monitoring studies of large-sized plastics items (i.e., meso- and macroplastics) and additives. For birds, reports of MPs in pellets or faeces were not considered because we focused on body burden only. According to Miller et al. (2020), the lack of polymer assignment of putative MPs with a validated laboratory method (e.g., FTIR or Raman Spectroscopy, or gas chromatography-mass spectrometry) was not considered as an exclusion criterion as this would have resulted in the exclusion of too many reports from the dataset. At the end of preliminary procedures, 179 publications remained for further assessment of eligibility. Full-text articles were analysed to extract both qualitative (i.e., information on the shape, colour and polymeric composition of MPs ingested by organisms in terms of percentage frequency) and quantitative (i.e., the body burden of MPs) data of MP bioaccumulation in different taxonomic groups. To allow a consistent comparison of MP body burden in different taxonomic groups, we considered two variables, namely the amount of MPs *per* individual (i.e., MPs/individual) and the number of MPs *per* wet weight (i.e., MPs/ww). The presence or absence of MPs in organisms was not considered a dichotomous variable. For all the taxonomic groups (except for zooplankton, see below) only data of MP contamination measured on taxa identified at least at the genus level were considered. In most cases, data on MP contamination at the species level were used, while in very few cases data from studies reporting MP body burden in organisms identified at the genus level (when the species name was not reported) were considered. Data reporting MP contamination as the mean body burden of multiple genera/species were excluded. This criterion was not applied to the zooplankton because the vast majority of the studies did not identify organisms at the genus or species level, reporting MP levels measured in pools of different zooplanktonic organisms (including fish larvae). Datapoints that were not reported in the units mentioned above (e.g., data reported in percentage, or with no quantification of the number of items isolated) were removed from the analyses. At the end of this procedure, 141 publications containing 793 data on MPs body burden were selected (see Appendix A). In detail, 180 data on MPs/ww from 46 studies, and 613 data on MP/individual from 128 studies were included in the qualitative and quantitative assessment. However, four data points (two on MP/ww and two on MP/individual) from a single study (Curren et al., 2020) were excluded from further analyses (but see the Discussion section) because they were extremely high (i.e., three orders of magnitude above the mean values), and their inclusion would have affected any reliable conclusion. These extreme MP values were recorded in the Pacific white leg shrimp *Litopenaeus vannamei* and the Indian white prawn *Fenneropenaeus indicus* fished in Malaysia, Ecuador, Southwest Atlantic, and the Indian Ocean and bought in Singapore market (Curren et al., 2020). Lastly, information on the geographical origin of the organisms and, when available, the shape and the polymeric composition of MPs were extracted. We did not extract the size of the MPs because of the large inconsistency of size ranges among the studies.

2.2. Statistical analyses

To analyse the variation in MP body burden expressed as MPs/individual and MPs/ww according to taxonomy and latitudinal bands, we relied on linear mixed models (LMMs) that were interpolated using the *lmer* function of the lme4 package (Bates et al., 2015) implemented in R (version 3.2.1; R Core Team, 2019). The models included a five-level fixed factor denoting the taxonomic group (i.e., zooplankton, bivalves, crustaceans, fish, and other vertebrates). The category named 'Other vertebrates' included data on MP contamination in organisms such as reptiles, birds and mammals, because of the limited number of studies that investigated the body burden of MPs in these taxa and because they ingest these contaminants from the same ways (i.e., the diet and air-breathing). As accurate GPS coordinates were not available for many studies, a three-level fixed factor indicating whether each datum was collected in the tropical (i.e. between the Tropic of Cancer at latitude 23° 27′ N and the Tropic of Capricorn at latitude 23° 27′ S), subtropical (i.e. between the Tropics and polar circles at latitudes ranging between 23° 27′ N and 66° 33′ N, and 23° 27′ S and 66° 33′ S) or polar (i.e., latitudes>66° 33′ N and 66° 33′ S, respectively) regions (hereafter 'latitudinal band'). The MPs/ww dataset included a single datum from a study performed in polar regions and one from a pool of samples from different areas worldwide: both these data were removed from statistical analyses (but were included in the qualitative data description). We also included the year of publication of each study as a covariate to test for temporal variation in MP contamination, possibly reflecting a change in environmental plastic pollution and/or an improvement in MP detection procedures. As many studies reported multiple data, we also included the identity of the study as a random factor to account for the non-independence of data collected by single studies (i.e., same authors, same location, and same analytic methods).

For all models, estimated marginal means and pairwise comparisons among the levels of each fixed factor (i.e., taxonomic group and latitudinal band) were estimated with the package *emmeans* by using the Kenward-Roger method for degrees of freedom estimate and the Tukey method for P-value adjustment (Buerkner et al., 2020) Correlation among fixed factors and the presence of outliers were checked using the package *performance* (Lüdecke et al., 2021). The variance inflation factor was always smaller than 2, thus showing no collinearity among predictors. Five and 18 outliers were removed from statistical analyses of MP/ww and MP/individual analyses, respectively. The final dataset was therefore composed of 593 MP/individual data (from 119 studies) and 175 MP/ww data (from 43 studies). The distribution of both dependent variables was far from normal, therefore we used a square root transformation to better approximate a normal distribution.

3. Results

The 140 studies that satisfied the eligibility criteria contained 789 data, including the statistical outliers (611 in terms of MPs/individual and 178 in terms of MPs/ww; mean number of data per study: 5.56 ± 8.01 SD), but excluding Curren et al. (2020). Ninety-five papers (68%) reported information on MPs/individual only, and 13 on MPs/ww only (9%), while 32 papers (23%) reported both variables. Among these studies, 7 (28 data) contained information on MP contamination in zooplankton (5.0% of the total number of publications; 3.5% of total data), 40 (136 data) in bivalves (28.6%; 17.2%), 26 (63 data) in crustaceans (18.6%; 8.0%), 76 (530 data) in fish (54.3%; 67.2%), 3 (13 data) in reptiles (2.1%; 1.6%), 1 (2 data) in birds (0.7%; 0.3%) and 8 (17 data) in mammals (5.7%; 2.2%).

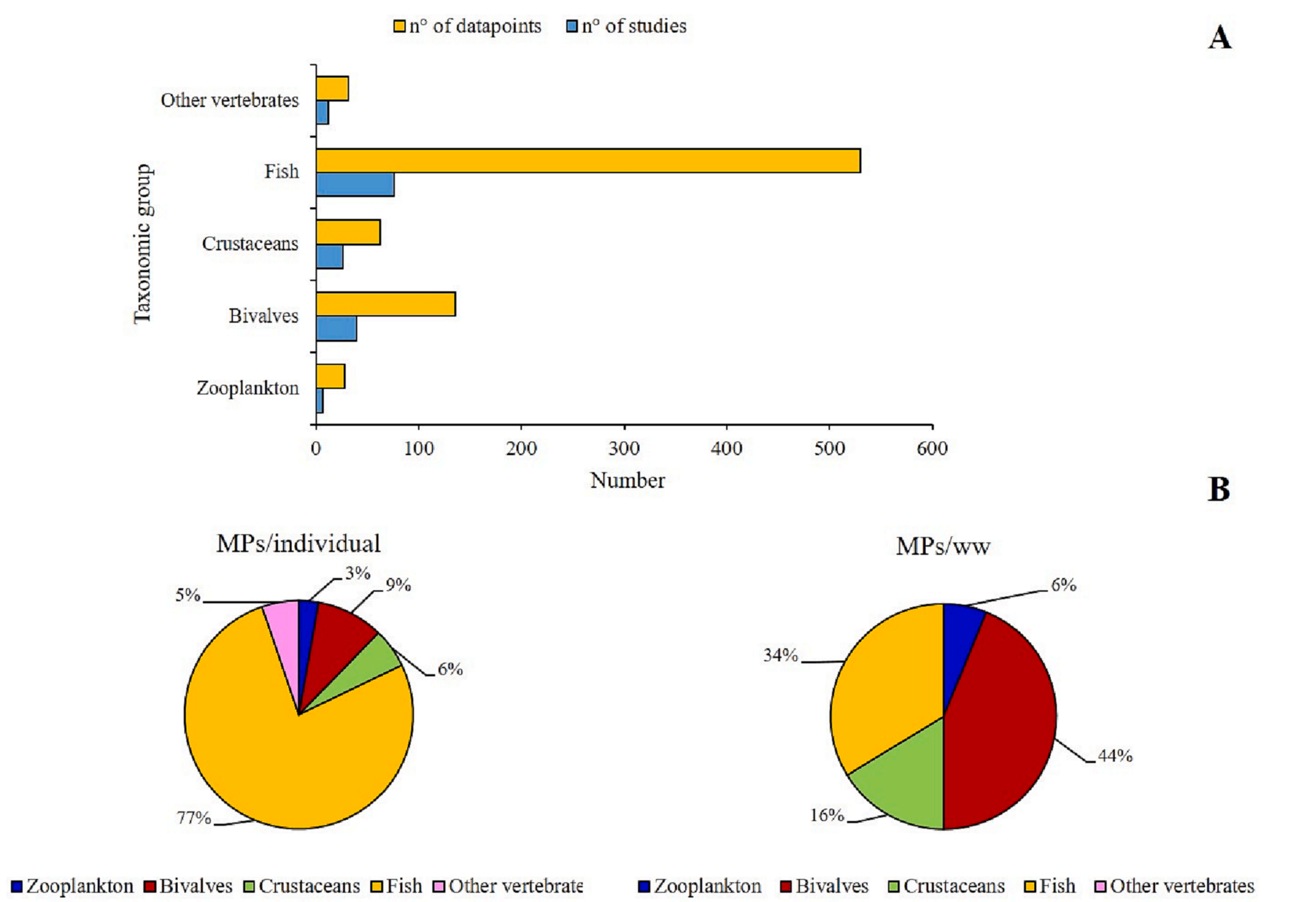

Fig. 1. Number of studies and datapoints included in the analysis grouped per taxonomic group (a), percentage of data per each taxonomic group expressed as mps/individual or mps/ww (b).

Data availability was rather different among taxonomic groups (Fig. 1). MPs/individual data were available for 470 fishes (76.9%), 58 bivalves (9.5%), 34 crustaceans (5.6%), 17 zooplankton organisms (2.8%), 17 mammals (2.8%), 13 reptiles (2.1%) and 2 birds (0.3%), while MPs/ww data were available for 78 bivalves (43.8%), 60 fish (33.7%), 29 crustaceans (16.3%) and 11 zooplankton individuals (6.2%). Overall, fish was the most investigated taxonomic group, followed by bivalves, crustaceans, and zooplankton, while a limited number of studies focused on reptiles, birds and marine mammals (Figs. 1 and 2). This is the main reason why we used 'vertebrates other than fish' in the analyses as a single category (i.e., other vertebrates). In addition, the proportion of data reporting MP/individual was larger than that reporting MP/ww for all the taxonomic groups (crustaceans: 54.0%; zooplankton: 60.7%; fish: 88.7%; reptiles, birds, and mammals: 100%), except for bivalves (42.6%). Data of MP/individual is the only information for birds, reptiles, and mammals.

Field studies of MPs accumulation in marine organisms were performed on 347 genera (excluding zooplankton) belonging to different taxonomic groups, whereby 262 were fish (75.5%), 32 bivalves (9.2%), 31 crustaceans (8.9%), 14 mammals (4.0%), 6 reptiles (1.7%), and 2 birds (0.6%). Independently of the taxonomical group, most of the studies were performed in the sub-tropical latitudinal band (522 data in 97 studies; 66.2% and 69.3% respectively), followed by the tropical latitudinal band (249 data from 39 studies; 31.6% and 27.9% respectively), while only a limited number of studies collected organisms from the polar regions (17 data from 8 studies; 2.2% and 5.7% respectively). A single study collected samples from diverse locations across the globe. Fig. 2 shows data distribution across taxonomic groups and latitudinal bands.

No contamination in terms of MPs/individual was detected in 95 cases (15.5%), mainly fish (89 cases), and equally distributed between tropical (53 cases) and subtropical (42 cases) latitudinal bands. No contamination in terms of MPs/ww was observed in only 5 cases (2.8%), 4 of which were crustaceans and 1 was in bivalves, located in the tropical (4 cases) and subtropical (1 case) latitudinal bands. Independently of the latitudinal band, a large variability among taxonomical groups was noted in the MP body burden. Considering all the data extracted from studies that met the eligibility criteria, and including all the statistical outliers, the mean (±SE) of MPs/individual across all the taxa was 5.24 ± 1.21 (n = 611), while the average values of each taxon were 0.13 ± 0.06 for zooplankton (n = 17), 8.21 ± 2.00 for bivalves (n = 58), 30.04 ± 17.39 for crustaceans (n = 34), 2.68 ± 0.79 for fish (n = 470) and 13.90 ± 3.73 for other vertebrates (n = 32). Considering contamination expressed as MPs/ww, the mean (±SE) across all the taxa was 6.67 ± 3.05 (n = 178), while the values of each taxon were 13.59 ± 8.95 for fish (n = 60), 5.05 ± 1.87 for crustaceans (n = 29), 2.84 ± 0.50 for bivalves (n = 78) and 0.28 ± 0.05 for zooplankton (n = 11).

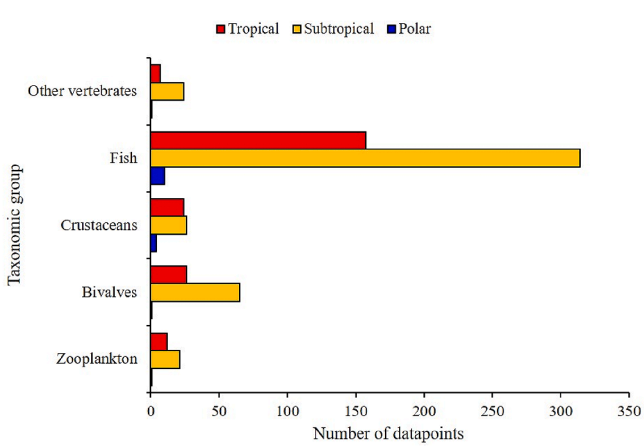

Fig. 2. Number of datapoints extracted from selected studies grouped per taxonomic group from different latitudinal bands.

Overall, the vast majority (>80%) of selected studies reported data on the colour and shape of MPs, while only 62% confirmed the polymeric composition of items that were isolated as putative MPs. Grouping MPs according to their shape (i.e., fibres, fragments, film, pellet/beads, and foam), fibres were dominant in all the taxonomic groups, accounting on average for 56% of the total amount of MPs, followed by fragments (31%), films, pellets/beads (9% for both the shapes), and foams (4%). This distribution was consistent in all the taxonomic groups. Concerning the colour, blue (20%), black (15%), and transparent (14%) MPs were more abundant compared to white (8%) and differently coloured MPs (4–8% depending on the colour). Isolated MPs were composed of different polymers. On average, polyolefins dominated the fingerprint of MPs contamination (38% of the total amount of polymers), whereby polystyrene (PS), polypropylene (PP), and polyethylene (PE) accounted for 20%, 18% and 10% of this polymeric class, respectively), followed by polyethylene terephthalate (PET)/polyester and polyamide (PA) (16% and 9%, respectively). Interestingly, 22% of the fingerprint was represented by natural polymers, such as cellophane or cellulose, which should not be included in the MPs count.

3.1. Taxonomic, spatial, and temporal variation in MPs body burden

A large, significant difference among taxa was observed in the number of MPs/individual ($\chi^2 = 77.83$, df = 4, $P < 0.0001$). In particular, the highest MPs body burden was observed in vertebrates other than fish, while the lowest one was found in the zooplankton (Fig. 3A). Vertebrates other than fish showed a significantly larger MP body burden than all the other taxonomic groups ($t_{142} \geq |5.64|$, $P \leq 0.0001$ in all cases), while the levels measured in the zooplankton were significantly lower compared to all the other groups ($t_{446} \geq |2.98|$, $P \leq 0.025$ in all cases; Fig. 1a). No pairwise differences were observed among bivalves, crustaceans, and fish ($t_{391} \leq |2.65|$, $P \geq 0.07$ in all cases; Fig. 3A). Differences among taxonomic groups were maintained when the group 'other vertebrates' was removed ($\chi^2 = 31.91$, df = 3, $P < 0.0001$), with significantly lower MP body burden measured in the zooplankton compared to the other groups, and also when the 18 outliers were included in the analyses ($\chi^2 = 27.22$, df = 4, $P < 0.0001$).

No latitudinal and temporal variations in MP body burden expressed as MPs/individual were observed (latitudinal band: $\chi^2 = 2.10$, df = 2, P = 0.35, Fig. 4A; year: $\chi^2 = 0.79$, df = 1, P = 0.37, data not shown), indicating a rather homogeneous body burden of MPs in organisms collected across the globe.

Differently from the analyses of the number of MPs/individual, no significant variation in the MP body burden expressed as MPs/ww occurred among taxonomic groups ($\chi^2 = 0.93$, df = 3, P = 0.82; Fig. 3B). However, no data for vertebrates other than fish was available for this variable. In addition, and consistently with the analyses on MPs/individual variable, no latitudinal and temporal variation in MPs/ww was observed (latitudinal band: $\chi^2 = 0.019$, df = 1, P = 0.89, Fig. 4B; year: $\chi^2 = 0.88$, df = 1, P = 0.35, data not shown).

4. Discussion

The present study summarized the results of a vast literature concerning the bioaccumulation of MPs in marine organisms belonging to different taxonomic groups at the global level. Significant differences in MPs bioaccumulation were observed among the groups, but only in MP/individual and not in MP/ww, while no temporal and geographical differences were noted in global contamination.

4.1. Taxonomic differences in MPs bioaccumulation

A large number of monitoring surveys has explored and confirmed that, at a global level, all marine organisms at different levels of the trophic web can efficiently ingest and bioaccumulate a wide array of

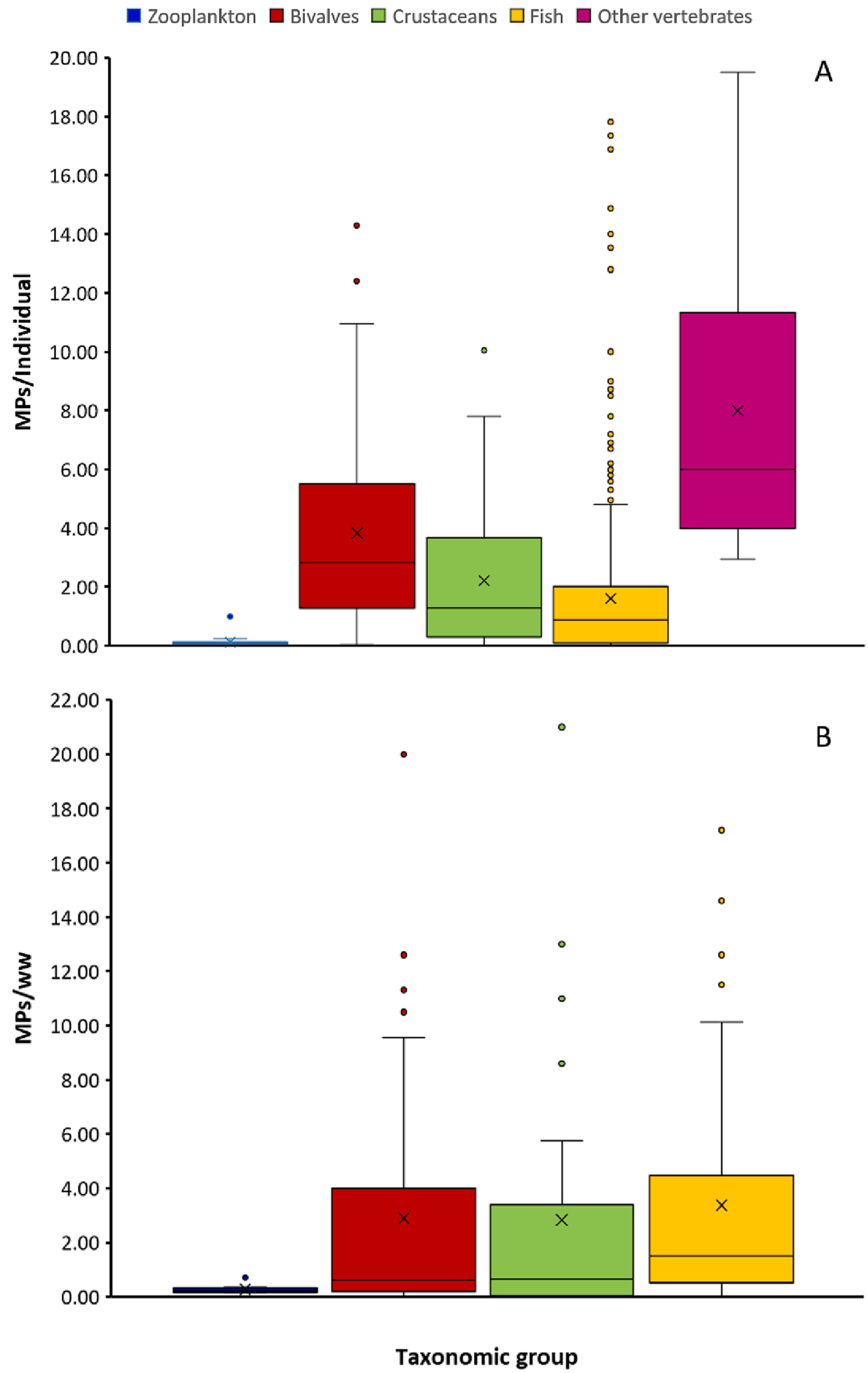

Fig. 3. Box plots showing the distribution of mps/individual (a) and mps/ww (b) among different taxonomic groups. the symbol "×" indicates the arithmetic mean within each taxon. outliers were excluded from the graphs.

MPs, with different shapes, sizes, colours, and polymeric compositions (Miller et al., 2020; Prokić et al., 2021). Among these studies, diverse species of small and large crustaceans, molluscs, and fish were used as the most common ecological indicators to assess the presence and distribution of MPs in marine ecosystems worldwide (de Sá et al., 2018; Prokić et al., 2021). In contrast, despite their crucial role in the food webs and in determining the fate of MPs due to trophic transfer, the information concerning low-sized organisms (e.g., phyto- and zooplankton) and large vertebrates other than fishes (i.e., reptiles, birds, and mammals) are scant (de Sá et al., 2018; Prokić et al., 2021).

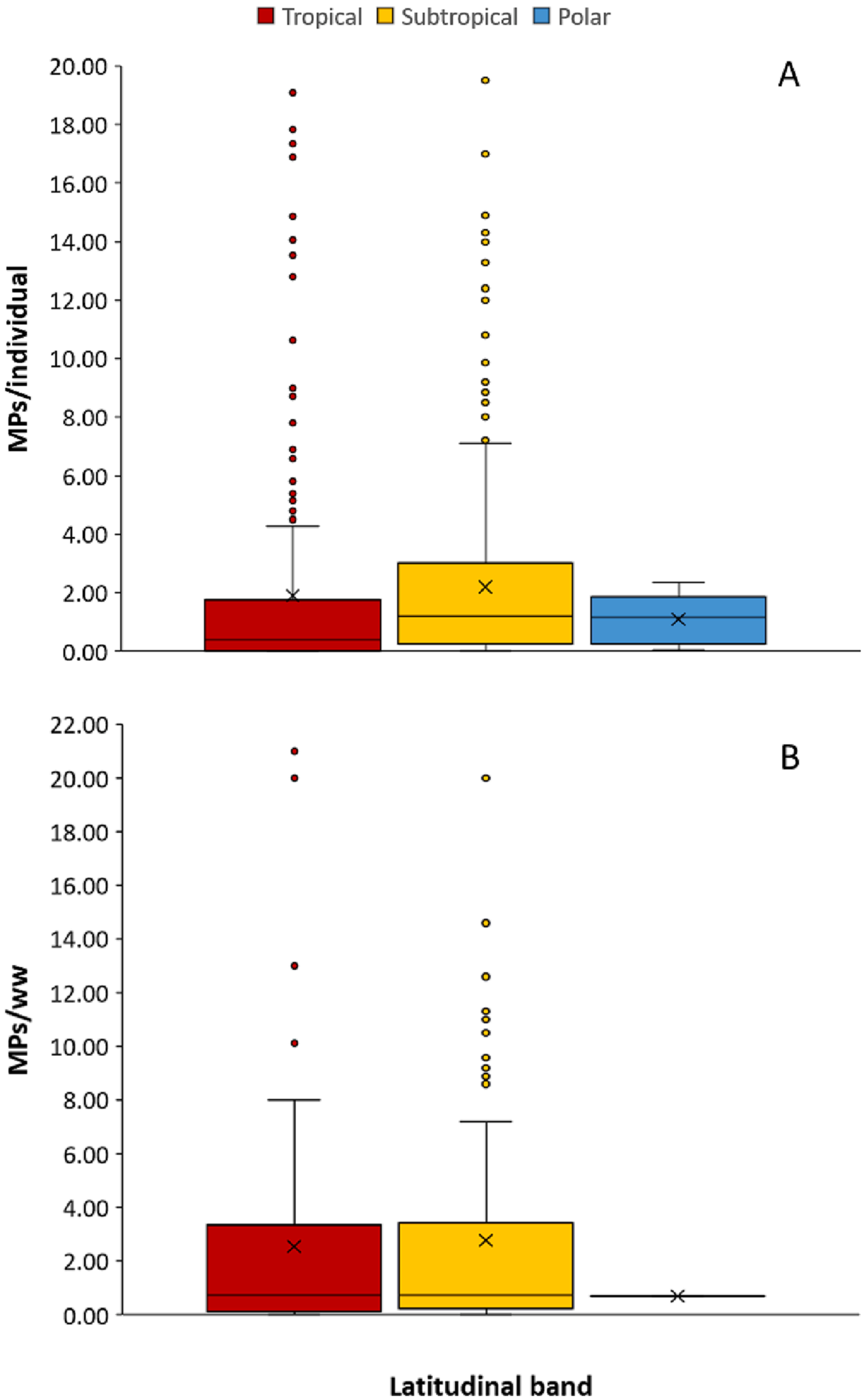

Fig. 4. Box plots showing the distribution of mps/individual (a) and mps/ww (b) among different latitudinal bands. the symbol "×" indicates the arithmetic mean within each taxon. outliers were excluded from the graphs. the single datum of the polar region in the mp/ww is shown for completeness, but was not used in the statistical analyses.

Moreover, these studies showed a huge within and among species (or genera) variability in MP body burden depending on intrinsic features of the MPs (e.g., size, shape, buoyancy or colour) or ecological (e.g., position in the water column, trophic level; Miller et al., 2020) and eco-physiological (e.g., uptake efficiency, ability to tolerate environmental stress, ecological niche, feeding type, behavioural plasticity, and life history strategies; Haegerbaeumer et al., 2019) characteristics of the organisms used as sentinels of contamination. Our quantitative review confirmed the large variability in MPs bioaccumulation in marine organisms belonging to different taxonomic groups. Independently of the geographical area of origin and year of sampling, vertebrates other than fish bioaccumulated higher levels of MPs (in terms of MPs/individual only) than all the other taxonomic groups. In contrast, zooplankton showed a lower body burden compared to the other taxa. Despite a large variability in MP body burden, no significant pairwise differences were noted among bivalve molluscs, crustaceans, and fish. The lack of differences in MP body burden between bivalves and crustaceans is not surprising considering that these taxonomic groups include species sharing similar ecological features, such as the type of feeding (most are filter feeders), their widespread presence in marine ecosystems, and their role in the trophic web (most of them are primary consumers; Garrido Gamarro et al., 2020). In contrast, fish were expected to be more contaminated than invertebrates because, such as all vertebrates, they are generally long-lived and positioned higher in the food chain (Bhagat et al., 2020). The lack of significant differences in MP body burden between fish and bivalves or crustaceans might be due to the high intra- and interspecific variability in ingestion and accumulation of MPs, as also indicated by the large variability in the data of MP bioaccumulation (especially for MPs/individual; see Fig. 3). Different feeding strategies and positions in the trophic web, as well as the growth rate and the size of fish species, can affect the MPs accumulation. Recent studies have demonstrated that the ingestion, the gut concentration, and the occurrence rate of MPs in fish did not increase with trophic level (Walkinshaw et al., 2020; Gouin, 2020; Miller et al., 2020; Covernton et al., 2021). However, it has been suggested that marine species at the lower trophic level are prone to suffer a greater risk of MP ingestion than those at higher ones (Walkinshaw et al., 2020). In fish, small, planktonic feeders might experience the greatest risk of ingesting and may accumulate the highest concentrations of MPs in their digestive tracts because of their ecological features (Collard et al., 2017). For instance, clupeids such as anchovy, sardines, and sprats, are generally mid-water feeders that either selectively ingest phytoplankton and/or zooplankton, or semi-selectively filter particles from the water column using their gill rakers, while often they can switch between the two feeding strategies (James, 1988). Clupeids showed higher (more than twice) concentrations of MPs in their digestive tracts compared to other fish families, with levels $>$ 10 items/individual (Covernton et al., 2021). These findings suggest that feeding strategies can be considered stronger drivers of MP ingestion and accumulation than the position in the trophic web (i.e., trophic level). Indeed, previous analyses showed neither a strong increase nor a decrease in MP concentration in the digestive tract of fish with trophic level (Covernton et al., 2021). In addition, the high variability observed in fish MP body burden can be due to the different sizes and/or ages of organisms. During different ontogenetic stages, organisms might differ in the rate of MP ingestion and accumulation, as well as in the response to MP exposure (Alomar et al., 2017; Steer et al., 2017; Bernardini et al., 2018; Pannetier et al., 2020). The body growth experienced by an organism during its lifespan represents one of the main factors affecting the rate of MP accumulation (Prokić et al., 2021). Thus, the larger body size achieved by adults or older individuals required a greater amount of food intake and consequently a larger MP accumulation. A minor effect of body size on MP body burden in the fish digestive tract, as well as a weak positive correlation with MP occurrence rate was noted, suggesting that larger fish are more prone to ingest MPs, but they do not necessarily retain more MPs in their digestive tracts (Covernton et al., 2021). The role of body size in ingesting and accumulating MPs was particularly clear in vertebrates larger than fish, whose MPs body burden was significantly higher compared to all the other taxonomic groups. However, a proper statistical test investigating the role of body size was unfeasible with the present data because each taxonomic group has a typical average size thus making the two variables (body size and taxon) almost coincident. A more detailed analysis *within* each taxonomic group is, therefore, necessary to disentangle the effects of body size and taxon. Moreover, although no clear evidence of biomagnification was observed (Miller et al., 2020), vertebrates such as seabirds, turtles, and cetaceans encompass species at the top of the trophic chain that can accumulate MPs via trophic transfer through the ingestion of contaminated preys. Furthermore, we can also speculate that higher levels of MPs observed in the digestive tract of vertebrates other than fish can be due to the fragmentation of large-sized plastic items (i.e., macro- and *meso*-plastics; Hartmann et al., 2019) that they can ingest or interact with. Indeed, the ingestion of large plastic items was confirmed for several species of marine vertebrates, including mammals, birds, and turtles (López-Martínez, et al., 2021 and references therein). In contrast, the low MP body burden observed in the zooplankton might be due to their small body size, which might preclude the ingestion (and consequent accumulation) of MPs bigger than the food they can ingest and/or may induce the obstruction of the digestive tract, decreasing feeding activity through a false sense of satiation (e.g., Cole et al., 2013; Welden and Cowie, 2016; Suwaki et al., 2020). The taxonomic differences and large within-group variability in MP body burden can be also due to different retention times (i.e., the duration of MP permanence in the digestive tract between ingestion and excretion; Klangnurak and Chunniyom, 2020) of MPs in the body of marine organisms. Reporting the body burden of MPs in organisms without information on the retention time of the indicator species and the contamination levels of the surrounding environment provides only snapshots information on MP accumulation (Klangnurak and Chunniyom, 2020). Laboratory experiments observed that the retention time of MPs in the digestive tract widely differs among taxonomic groups. For instance, the retention time calculated for the shore crab *Carcinus maenas* was 14 days (Watts et al., 2014), for the blue mussel *Mytilus edulis* was 48 days (Browne et al., 2008), while for two muddy shore (*Amphibalanus amphitrite* and *Fistulobalanus albicostatus*) and an epibiotic (*Chelonibia testudinaria*) barnacle species was lower than 200 min (Yu et al., 2021). Theretention time of MPs in the gastrointestinal tract of fish and vertebrates other than fish remains unclear. Thus, organisms with a high uptake and long retention time can accumulate more MPs compared with others with the same uptake rate but a shorter retention time (Klangnurak and Chunniyom, 2020).

Despite the large variability in MPs body burden, a qualitative analysis of data returned the consistent information that the dominant shape of MPs ingested by marine organisms was fibres. This result agreed with those reported in previous surveys of MPs contamination in the marine environment, showing that fibres were the most abundant shape of MPs in intertidal ecosystems (Mizraji et al., 2017), deep-sea sediments (Woodall et al., 2014), and surface waters (Hale et al., 2020). Moreover, fibres with a larger length-to-diameter ratio can be more likely retained within the organisms, resulting in a subsequent larger bioaccumulation and body burden (Qiao et al., 2019). MPs were mainly blue, black, or transparent, consistently with the results from the survey by Martí et al. (2020) showing that 47% of thousands of floating plastic items from a global collection were identified as clear/transparent and black. Our analysis confirmed that, independently of the shape and size of MPs, polyolefins such as PS, PP and PP, were the prevalent polymers in all taxonomic groups, followed by PET/polyester and PA. The fingerprint of contamination observed in organisms is similar to that observed for MPs floating or sinking in marine environments (Watt et al., 2021) and reflects the global demand of plastic polymers (PlasticsEurope, 2019).

4.2. Spatial and temporal variation of MPs accumulated in biota

The MP contamination in marine ecosystems has been monitored by measuring the number of buoyant plastics floating at the sea surface worldwide (Hale et al., 2020). MP contamination was extensively surveyed in the Western North Atlantic Ocean (Law et al., 2010) and the Eastern North Pacific Ocean (e.g., Goldstein et al., 2012; Law et al., 2010). In contrast, the presence and distribution of MPs in the Southern hemisphere gyres (Eriksen et al., 2014, 2013; Cózar et al., 2014) and in the vast majority of the sea surface outside the gyres remain unsurveyed, precluding the opportunity to estimate the contamination of floating MPs at the global scale. However, a recent modelling study showed that the presence (and concentration) of MPs at global scale was localized in the centres of the subtropical gyres, mainly in the North Atlantic and North Pacific oceans, where plastic debris accumulate because of the convergence of Ekman transports (Kubota 1994; van Sebille, 2015). Lower occurrence and concentrations were observed in the tropics, and poleward of 45° S and 45° N (van Sebille et al., 2015). Accordingly, the models estimated that the MP counts and mass have similar patterns, with high values in the subtropics and low values in the tropics and at high latitudes (van Sebille et al., 2015). The highest concentrations measured and modelled in the subtropical gyres, with the largest mass reservoir in the North Pacific Ocean, are likely due to the vast extension of this area and the large inputs of plastic waste from the coastlines of Asia and the United States (Jambeck et al., 2015). Despite these data, our analyses did not highlight any clear geographical distribution of MPs accumulated in the biota. According to observational and modelling data, we could expect that organisms from subtropical areas accumulated more MPs compared to organisms from tropical and polar ones. However, independently of the taxonomic group, no significant differences in MPs body burden, neither expressed as MPs/individual nor MPs/ww, were found in organisms from different latitudinal bands. These results can be due to the large variability in MPs bioaccumulation among different taxonomic groups. Moreover, the presence of hot spots of contamination in tropical areas can result in a very high bioaccumulation and consequently in an overdispersion of data. An alternative explanation of the discrepancy between the levels of MPs measured in surface seawater and in the biota might be referred to the biological indicator used in biomonitoring operations. Indeed, benthic or demersal species can ingest and accumulate also sinking MPs excluded from measurements and modelling of surface waters contamination.

No temporal differences in MPs body burden were noted, independently of the taxonomic group and the geographical origin of the samples. The large variability of MP levels, likely due to the lack of standardization of methodological and analytical approaches used to isolate and identify MPs, might have masked possible temporal differences in MP contamination, as suggested by a recent review performed on bivalve molluscs that observed significant temporal differences in the abundance of accumulated MPs over 7 years, but no clear temporal trends (Ding et al., 2022).

5. Conclusions

This review provides a global perspective of the current studies on MP contamination in marine organisms, discussing differences in bioaccumulation mainly due to taxonomy and geographical origin. Our analysis showed that the MP body burden differs among taxonomic groups, with zooplankton and vertebrates other than fish showing the lowest and the highest amount of accumulated MPs, respectively. Despite these differences, the huge within-taxonomic group variability observed for bivalve molluscs, crustaceans, and fish precluded the opportunity to shed light on potential differences in bioaccumulation among them and other taxonomic groups. Our findings suggest that all marine organisms can be used as ecological indicators of MPs contamination, but the large variability in body burden within each taxonomic group does not allow to shed light on geographical patterns of contamination at the global level. Different factors can be identified to explain such variability. The main key factor is related to the huge differences in the approaches used to collect and to process the samples for isolating and characterizing the MPs ingested and accumulated by marine organisms. Overall, the analyses of our dataset suggest the urgent need for harmonization and standardization of sampling, isolation, and identification methods for MPs analysis in different organisms, to allow a robust inter-comparability of findings across studies. Sampling strategies need to be carefully elaborated, mainly for sampling time and sample size, and the protocols of MP isolation unified, at least within each taxonomic group. Quality assurance (QA) and quality control (QC) protocols represent a crucial step in MP analysis (Cowger et al., 2020), but field studies were often performed without a method validation and/or the inclusion of field and laboratory blanks in batches of analyses. The lack of QA/QC should result in underestimations or overestimations of MP body burden in samples collected in the field because of low recoveries of the methods or external contamination due to sampling operations and/or laboratory procedures. Overestimation of MP body burden might also depend on the lack of proper identification of the polymeric composition of each isolated item, which needs to be considered as a putative MP before chemical characterization. The characterization of the polymeric composition represents a crucial analytical step because it allows disentangling items made of synthetic, plastic polymers from natural ones, such as cellulose or cellophane, preventing overestimations of MP body burden and reducing the variability of the measures. Thus, harmonization of procedures for MP identification is necessary to exclude items made of natural polymers from the counts. To confirm the extent of bioaccumulation and to compare the results among different taxonomic groups from different geographical areas, further studies should be addressed to explore differences in uptake efficiency and in retention time, as well as to assess the abundance of MPs in seawater and/or sediments from the same areas where the organisms were sampled. In conclusion, harmonization and standardization of methods and procedures of MPs analysis are mandatory to enlarge the knowledge on the uptake and accumulation processes for organisms used in biomonitoring surveys. Indeed, harmonic data of MP accumulation in organisms can help identifying suitable ecological indicators to assess contamination levels and temporal trends and to shed light on the distribution patterns at the local and global scales, as well as to estimate the exposure levels and the potential effects for the biota. Therefore, methodological and technical improvements of MP biomonitoring in the field should allow making recommendations for improving the environmental management of marine ecosystems.

CRediT authorship contribution statement

Marco Parolini: Conceptualization, Data curation, Investigation, Supervision, Writing – original draft, Writing – review & editing. **Matteo Stucchi:** Investigation, Data curation, Writing – review & editing. **Roberto Ambrosini:** Formal analysis, Writing – review & editing. **Andrea Romano:** Data curation, Formal analysis, Writing – original draft, Writing – review & editing.

Declaration of Competing Interest

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

Data availability

Data will be made available on request.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ecolind.2023.110179.

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