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What do we know about how the terrestrial multicellular soil fauna reacts to microplastic?

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Abstract. The ubiquitous accumulation of microplastic (MP) particles across all global ecosystems accompanies their uptake into soil food webs. In this review, we analyzed studies on passive translocation, active ingestion, bioaccumulation and adverse effects within the phylogenetic tree of multicellular soil faunal life. The representativity of these studies for natural soil ecosystems was assessed using data on the type of plastic, the shape, the composition, the concentration and the time of exposure.

Available studies cover a wide range of soil organisms, with emphasis on earthworms, nematodes, springtails, beetles and lugworms, each focused on well-known model organisms. Thus, about 58 % of the studies used inappropriate concentrations or units, whereas 42 % applied MP concentrations similar to amounts in slightly to very heavily polluted soils. In many cases, however, polystyrene microspheres were used, which represent a combination of plastic type and shape that is easily available but does not reflect the main plastic input into soil ecosystems. In turn, MP fibers are strongly underrepresented compared with their high abundance within contaminated soils. A few studies also examined the comminution of macroplastic by the soil fauna. Further properties of plastic such as aging, coating and additives have been insufficiently documented. Despite these limitations, there is a recurring pattern of active intake followed by a population shift within the gut microbiome and adverse effects on motility, growth, metabolism, reproduction and mortality in various combinations, especially at high concentrations and small particle sizes.

For the improvement of future studies, we identified the problems with past experiments, and we recommend that coming studies consider the type, shape, grade of aging, specific concentrations of MP fractions and long-term incubation in both natural and contaminated soils.

1 Introduction

Imagine a compact plastic cube with a length of almost 2 km and a weight of 7 300 000 000 t that comprises major percentages by weight of 36 % polyethylene (PE); 21 % polypropylene (PP); 12 % polyvinyl chloride (PVC); and 10 % polyethylene terephthalate (PET), polyurethane (PU) and polystyrene (PS), respectively. This was the accumulated global non-fiber production of the six main plastic types as of 2015, and amounts to 87 % of all-time plastic production. This production has evolved exponentially since the early 1950s from some megatons (Mt) to 8300 Mt as of 2015, with a 260 Mt annual output in 2009 increasing to a 380 Mt output in 2015 (Thompson et al., 2009; Geyer et al., 2017). From the total amount of plastic ever produced, 6300 Mt had become waste as of 2015; from this total amount only 21 % was recycled or incinerated, whereas 5000 Mt ended up in landfills and nature (Geyer et al., 2017). As a corollary of production, use and disposal, a certain part of plastic waste is constantly released into the environment via various pathways, but our knowledge about rates of mass flow into global ecosystems is very limited. Based on waste generation in coastal countries, Jambeck et al. (2015) calculated the global plastic input to marine ecosystems to be roughly 4.8 to 12.7 Mt in 2010.

Such data on soils are lacking, but Nizzetto et al. (2016) estimated that the load of microplastic (MP) to agricultural sites in Europe is of the same order of magnitude as that in marine environments.

By littering, plastic mulching, the application of sewage sludge, digestates and composts, and windblown dispersal (Bertling et al., 2018; Weithmann et al., 2018; Zhang et al., 2019; Wang et al., 2019a), plastic from our technosphere arrives in soil ecosystems in various forms as large and small fragments, fibers and particles. Due to exposure to UV radiation, mechanical stress and processing by soil organisms, plastic items become weathered and prone to a successive comminution towards the MP size range with increased surface, charge and biofilm cover (Kale et al., 2015; Andrady, 2017). However, the resistance of plastic to metabolization causes a constant accumulation in soils as long as the release rate from human processes is above the very slow rate of degradation.

Due to a lack of monitoring programs, data on MP concentrations in terrestrial soils are rare, and those using weight by weight (w/w) concentrations represent only a small part of the information available compared with item concentrations. In soils with only slightly contaminated conditions, amounts seem to average about $1\,\mathrm{mg\,kg^{-1}}$ soil dry weight (and approximately $200\,\mathrm{items\,kg^{-1}}$ dry soil; Rezaei et al., 2019). On sites with industrial activity or the intensive use of plastic mulch and sewage sludge for agriculture, concentrations can be increased by 2 to 4 orders of magnitude (Fuller and Gautam, 2016; Zhang and Liu, 2018; Huang et al., 2020). Semisubhydric soils such as beaches, mudflats, mangroves or lagoons, which are additionally contaminated from the aquatic side, contain MP concentrations of the order of 10–$100\,\mathrm{items\,kg^{-1}}$ dry soil, and single extreme samplings have been shown to contain several thousand items (Nor and Obbard, 2014; Naji et al., 2017; Garcés-Ordóñez et al., 2019; J. Li et al., 2018). More informative data using milligrams per kilogram are only available for beaches and coastal deconstruction yards in municipal neighborhoods and amount to 0.5 and $70\,\mathrm{mg\,kg^{-1}}$ dry soil and $0.00005\,\%\,w/w$ and $0.007\,\%\,w/w$, respectively (Reddy et al., 2006; Claessens et al., 2011). All of these concentration data represent a wide range of particle sizes between 0 and 5000 µm with different materials, shapes and degrees of aging.

Plastic particles can possibly enter and accumulate in the food web by either direct uptake from soil or by consumption of other soil biota that are contaminated by adhesion or ingestion (Huerta Lwanga et al., 2017a). There is evidence that MP is even incorporated by plants and unicellular organisms at the base of the food web. Bacteria, for example, which are reasonably assumed to avoid MP uptake due to their minor size and the prevalent lack of phagocytosis, have been shown to take up inorganic nanoparticles of a few nanometers in size (Kumar et al., 2011). Although the physiochemical properties of weathered nanoparticulate plastics might differ from these, their uptake also seems likely.

A similar argument can be made for fungi and soil algae, although studies on incorporation are lacking, whereas transfer into a freshwater food web by adhesion of nanoplastic on algae has been shown by Chae et al. (2018). The uptake of MP into plant roots is also inhibited (Rillig et al., 2019), but the permeation of nanoplastics into plant tissue has been reported (Li et al., 2019). However, the integration of MPs into root tissue after adsorption to the rhizodermis has yet to be studied.

In contrast, protozoa feature phagocytosis for the active ingestion of particles. Diverse soil, freshwater and marine ciliates ingest PS/latex beads from 0.1 to 14.4 µm in size in laboratory experiments, with a preference for their natural prey size (Fenchel, 1980; Jonsson, 1986; Lavin et al., 1990). Soil amoebas act similarly, but they additionally select according to food quality (Weisman and Korn, 1967; Vogel et al., 1980; Bowers and Olszewski, 1983; Avery et al., 1995; Elloway et al., 2006).

Finally, many soil microbiota live protected within biofilms. Plastic particles have been shown to be a potential surface for the formation of those biofilms (Lobelle and Cunliffe, 2011), which are a food source for grazing primary consumers. Inadvertent ingestion might also transfer occluded or abraded MP to higher trophic levels.

But what about the larger organisms that feed on these free plastic particles, contaminated microorganisms, biofilms and one another? Recent work has discussed the effects of MPs on soil biota (Chae and An, 2018) or has called for intensified research on certain taxonomic groups (Rillig and Bonkowski, 2018). Thus, we were motivated to carry out a review with a focus on the most highly produced plastics and their passive translocation, ingestion, bioaccumulation and adverse effects on the multicellular soil fauna. The types, sizes and shapes of plastic used in former laboratory studies have been compared with the available knowledge on plastic in the environment and recommendations are given for future research. This analysis aims to support the assessment of the influence of MPs on the ecosystem services provided by diverse soil organisms.

2 Search pattern

Within the tree of life, edaphic branches were identified comprising taxa that permanently inhabit the soil, taxa that are part of the soil food web and/or burrowing macro- and megafauna, and taxa that have active subterranean larval stages. The resulting tree of soil life based on the NCBI taxonomy database (Fig. 1) was drawn using phyloT software and shows the leading taxonomic rank, which is generally family, although in exceptional cases, e.g., if one species represents the only soil-dwelling stage between many aquatic stages, may be a lower rank.

A pattern of search terms was established (Table 1), consisting of “taxon” (Linné’s binominal nomenclature, com-

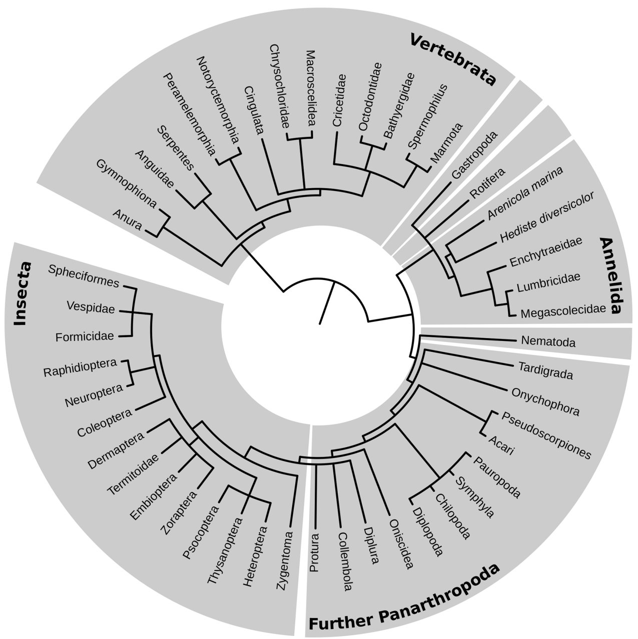

Figure 1. Tree of edaphic fauna. Taxonomic ranks that were examined in this qualitative study are shown on the outer rim of the diagram. The length of the connecting line between two taxa represents the grade of the phylogenetic relationship.

mon name, plural-sensitive search), "plastic type" (plastic, microplastic, nanoplastic, PE or polyethylene, PP or polypropylene, PVC or polyvinyl chloride, PS or polystyrene, PU or polyurethane, PET or polyethylene terephthalate, and latex) and "common shapes" (fragments, particles, fibers, microfibers, beads, microbeads and microspheres). Some type–shape combinations caused problems, as they led to a very large amount of unuseful, off-topic papers, e.g., when using any taxon combined with PET, papers that used PET bottles in their experimental setups or studies on pets were selected. Therefore, these combinations of search terms were excluded from the search pattern. Further plastic types and shapes occurring within the studies that were found were also included in the review. Data on microspheres and microbeads were pooled, as both names describe the same thing.

The search was applied between June 2019 and January 2020 within the Web of Science Core Collection database; it was repeated in the first week of January 2020 and covers publications until January 2020. The search strings' result from the combinations of taxa, plastic types and particle shapes is shown in Table 1. Based on the search pattern, data on passive transport, ingestion, bioaccumulation and adverse effects were collected for each edaphic group. Studies that used uncommon, local, outdated or strange terms or nicknames were excluded by the search pattern. Studies testing injection to tissues, lymph or blood were excluded, as they do not represent natural ways of incorporating MPs. Data on MP inhalation by megafauna do represent a natural uptake process, but these studies were also excluded as they are exclusively related to aboveground organisms that only occur on the outer edge of the food web. Furthermore, running debates on phylogenetic classifications are not part of this work, and taxonomists will be able to adjust the branches according to their specific purpose.

The data on related taxonomic groups were pooled and evaluated for their environmental representativity based on exposure time, plastic concentrations and the properties used. From this synthesis, recommendations for a structured experimental design were derived for application in future studies.

3 Data collection

3.1 Insects

Within the Panarthropoda, the insects comprise the highest taxonomic diversity. Moreover, they represent an unevenly studied taxonomic group with respect to MPs.

Within the Insecta, the Coleoptera (beetles) are an extraordinarily diverse and abundant taxon. Studies on plastic uptake by adult individuals have mainly focused on the subfamily Scarabaeinae (dung beetles). Comprehensive experiments with latex microbeads have shown that many species only ingest smaller particles with maximum diameters of about 10–83 µm and retain them within the gut – with a slightly positive dependence on body size. Larger particles were rejected by a filtering mechanism within the mouth region and were not ground by the mandibles (Holter, 2000; Holter et al., 2002; Holter and Scholtz, 2005). Beside the information on nematodes, these data comprise the most detailed information (by far) about the size-dependent uptake of MP particles compared with other edaphic taxa. This provides a good foundation for future studies on adverse concentrations. In addition, several studies that have used plastic as the predominant food source have shown chewing, ingestion and intestinal degradation of different PS and PE foams in feeding experiments with *Tenebrio* sp. larvae (mealworms). These experiments have also pointed out an alteration of the gut microbiome, although no adverse effects on reproduction and survival have been reported – with only one observed case of a nonsignificant tendency toward higher mortality after 1 month of exposure (Yang et al., 2015, 2018; Brandon et al., 2018; Peng et al., 2019).

The Isoptera (termites), which were recently categorized as part of the order Blattodea, are the oldest social insects, with a tribal history of about 130 million years (Korb, 2008). Especially in arid ecosystems that lack earthworms, they play an important role in the homogenization of soils as well as in the sorting of soil mineral particles for building mounds and the decomposition and distribution of organic matter (De Bruyn and Conacher, 1990). Tsunoda et al. (2010) and Lenz et al. (2012) have shown that different termite species are picky feeders and that they erode PE but avoid other plas-

Table 1. Types and shapes of microplastic particles in edaphon studies within this review. The search on soil biota was carried out based on Linné's systematic names and common names. "×" symbolizes combinations excluded from the search pattern. The number counts show how often type–shape combinations were used in all reviewed experimental setups independently of organism. Empty fields denote zero results. The terms "microbeads" and "microspheres" are often used synonymously and are therefore counted together.

		Fragments	Particles	Fibers	Microfibers	Beads	Microbeads	Microspheres	Other, diverse, NA
Plastic	×								
Microplastic									
Nanoplastic									
PE or polyethylene	×	4	10	1	1	1			7
PP or polypropylene	×	1							
PVC or polyvinyl chloride	×	4	6	1					
PS or polystyrene	×	6	3				24	4	
PU or polyurethane	×								
PET or polyethylene terephthalate	×	3		2			×		
Latex	×				×		6		
Other		6	3		1			1	
NA		1		1		2		3	

NA stands for not available.

tic cable sheathings. This suggests the excretion of ground MP particles by termites, but the metabolic impacts are unknown. In contrast to termites, data on other Blattodea (e.g., cockroaches) were not found.

The suborder Apocrita comprises some flying insects that inhabit burrows within the soil such as ground-dwelling wasps within the Vespidae superfamily, mining bees within the Apoidea superfamily and the Spheciformes. They generally do not prey and feed on subterrestrial organisms, but they may move MP particles into the ground, as implied by a report from Allasino et al. (2019) on solitary bees that built nests made fully of plastic fragments. The Apocrita also contain the Formicidae (ants). Some ant species are considered an important vector for seed dispersal, which is a behavior that could also be shown for artificial plastic seeds with a diameter of ~ 2 mm (Hughes and Westoby, 1992; Angotti et al., 2018). Robins and Robins (2011) found that this also includes differently shaped cultural objects: *Rhytidoponera metallica*, a representative of ground-nesting, omnivorous ants, is not only capable of remarkable bioturbation but also of active, apparently random burying of anthropogenic plastic artifacts > 1 mm. Seeds are used as a food source; thus, the ingestion of plastic bites is conceivable but has not been documented. The uptake of latex microspheres ≥ 0.88 µm with liquids by *Solenopsis invicta* larvae seems to be prevented by filtration within the mouth, and the particles are released as larger aggregates, whereas other species ingest much larger particles up to 150 µm (Glancey et al., 1981). However, also here, data on adverse effects are missing.

Further insects with edaphic adult stages such as Dermaptera (earwigs), Heteroptera (true bugs) and Zygentoma (silverfish, fish moth and firebrat) or soil- or litter-dwelling larvae such as Embioptera (webspinners or footspinners), Thysanoptera (thrips), Psocoptera (booklice, barklice or barkflies), Neuroptera (lacewings), Raphidioptera (snakeflies) or Zoraptera (angel insects) have not yet been researched with a focus on soil MPs.

Regarding insects, mainly studies on the translocation and uptake of MP have been carried out. In contrast, work on bioaccumulation is completely lacking, and adverse effects have been sparsely tested using *Tenebrio* sp. larvae. Such studies could provide information on whether or not the input of MPs in soil ecosystems is one of many factors causing the global decline in entomofauna (Oliveira et al., 2019; Sánchez-Bayo and Wyckhuys, 2019).

3.2 Other panarthropods

Apart from the insects, Acari (mites) comprise many abundant soil-dwelling taxa that feed on litter, fungi and fauna as both predators and parasites; they are also bioindicators, as they are sensitive to changes in the soil physiochemical environment (Gulvik, 2007). Experiments have indicated that mites passively transport MPs by pushing and dragging after attachment to their cuticle, as shown with 80–250 µm sized PVC particles in a Petri dish experiment without soil (Zhu et al., 2018a). The population within manure pats slightly declines when exposed to millimeter-sized, unweathered PE and PS particles at concentrations of $5\,\%\ v/v$ and declines strongly at $\geq 60\,\%\ v/v$ (Stamatiadis and Dindal, 1990). This may be an effect of moisture deficiency due to a reduced water-holding capacity in an unnaturally enriched substrate but not necessarily due to plastic intake. In contrast, no data

Table 2. Microplastic studies on Coleoptera, Blattodea (Blattod.), Apoidea (A.) and Formicidae. The abbreviations used in the table are as follows: mb refers to microbeads, fr refers to fragments, ms refers to microspheres, b refers to beads, LD refers to low density, MD refers to medium density and NA denotes that information was not available. Concentrations refer to milligrams per kilogram dry soil unless indicated otherwise.

	Organism	Experimental environment	Plastic type	Aging	Coating	Additives	Shape	Size span (µm)	Concentrations	Exposure time	Passive transport	Active uptake	Bioaccumulation dynamics	Measured adverse effects	Reference
Coleoptera	*Aphodius erraticus*	Petri dish	Latex	NA	NA	NA	mb	5	NA	45 min	NA	No	NA	NA	Holter (2000)
	Aphodius rufipes							2–39				≤ 14 µm			
	Aphodius ater							2–39				≤ 14 µm			
	Aphodius fimetarius							2–39				≤ 18 µm			
	Aphodius contaminatus							2–39				≤ 18 µm			
	Aphodius fossor							2–39				≤ 18 µm			
	Diverse dung beetles	Vial	Latex	NA	NA	NA	mb	2–83	NA	45 min	NA	≤ 10–≤ 60 µm	NA	NA	Holter et al. (2002)
	Diverse dung beetles	NA	Latex	NA	NA	NA	mb	2–83	NA	45 min	NA	≤ 4–≤ 95 µm	NA	NA	Holter and Scholtz (2005)
	Tenebrio molitor larvae	Container	PS	NA	NA	No	Foam	NA	100 % w/w (food)	31 d	NA	Yes	Biodegradable	NA	Yang et al. (2015)
	Tenebrio molitor larvae	Petri dish	LD-PE PS	NA	NA	No Flame retardant	Foam	8–27 cm^3	50–100 % w/w (food)	32 d	NA	Yes	Biodegradable	Microbiome	Brandon et al. (2018)
	Tenebrio molitor larvae	Container	PS	NA	NA	NA	Foam	NA	4–100 % w/w (food)	32 d	NA	Yes	Biodegradable	No	Yang et al. (2018)
	Tenebrio molitor larvae	NA	PS	NA	NA	No	Foam	NA	86–100 % w/w	31 d	NA	Yes	Biodegradable	Microbiome	Peng et al. (2019)
	Tenebrio obscurus larvae								(food)						
Blattod.	*Coptotermes formosanus*	Mesocosm	LD-PE	Yes/no	NA	NA	Cable	4 cm,	NA	42 d	NA	Yes	NA	NA	Tsunoda et al.
			Others				sheaths	⌀ 0.8 cm				No			(2010)
	Diverse termites	In situ	MD-PE	No	NA	Antioxidant	Cable	30 cm,	NA	6 years	NA	Yes	NA	NA	Lenz et al. (2012)
			PA			Stabilizer	sheaths	⌀ 1.4 cm				No			
A.	*Megachile* sp.	In situ	NA	NA	NA	NA	fr	NA	NA	NA	Yes	NA	NA	NA	Allasino et al. (2019)
Formicidae	*Solenopsis invicta*	Petri dish	Latex	NA	NA	Fluorescence	ms	0.9–4.5	2.5 % w/w (food)	Direct	NA	Filtration	NA	NA	Glancey et al. (1981)
	Rhytidoponera metallica	In situ	NA	NA	NA	NA	b	NA	50 items	3 d	Yes	NA	NA	NA	Hughes and
	Aphaenogaster longiceps								per nest						Westoby (1992)
	Pheidole sp.														
	Rhytidoponera metallica	Mesocosm	NA	NA	NA	NA	Diverse	< 75.5 cm	NA	26 months	Yes	NA	NA	NA	Robins and Robins (2011)
	Diverse ants	In situ	NA	NA	Attractant	NA	b	1.8 cm	NA	1 d	Yes	NA	NA	NA	Angotti et al. (2018)

were found on their arachnoid, predatory relatives, Pseudoscorpiones (false scorpions).

Similar to many other highly abundant and diverse representatives of the soil mesofauna, the Oniscidea (woodlice) contribute to the decomposition of litter via chewing and passage through their digestive system (Warburg, 1987) and react strongly to environmental pollution; thus, they can potentially be used as bioindicators (van Gestel et al., 2018). They practice a strict selection of natural food sources (Hassall and Rushton, 1984). This is also demonstrated for starch- and cellulose-based plastic films ($4\,cm^2$), which were consumed and digested in experiments using the model organism *Porcellio scaber*, in contrast to PHB (polyhydroxybutyrate) films, which reduce the feeding rate (Wood and Zimmer, 2014). Smaller PE particles ($137 \pm 51\,\mu m$ and $183 \pm 93\,\mu m$) embedded in food pellets (0.4 % w/w) were taken up easily by *Porcellio scaber*, and the smaller fraction caused a slight, nonsignificant reduction of body mass after 14 d of exposure, but there was no observed impact on feeding, defecation or energy reserves (Kokalj et al., 2018).

Other panarthropodean groups are even less studied in terms of MPs. We did not find literature on the subphylum of Myriapoda, containing the Diplopoda (millipedes), Chilopoda (centipedes), Pauropoda and Symphyla (pseudocentipedes or symphilids) classes, which are important litter-feeders and predators within various soil ecosystems.

The situation is similar for the Tardigrada (water bears or tardigrades) phylum, which comprises many ecologically relevant and well-studied species that feed on microorganisms and detritus particles. Sparse field research in semisubhydric environments has shown no uptake of MP fibers by Tardigrada (Gusmão et al., 2016); however, comprehensive data on terrestrial soils are lacking. This is similar for the related phylum of Onychophora (velvet worms), primordial invertebrates that are mainly native in litter and soils with high water-holding capacity under Pleistocene-like forest vegetation within tropical and moderate regions (Monge-Nájera, 1994).

The phylum of Collembola (springtails), together with the orders of Diplura and Protura (Westheide and Rieger, 1996; Pass and Szucsich, 2011), are intensively studied morphological groups that exhibit similar ecological functions, such as the distribution and decomposition of organic matter as well as the control of fungal abundance (Hopkin, 1997). Springtails provide up to 27 % of the soil biomass and up to 33 % of the total soil respiration (with higher shares in colder ecosystems; Petersen, 1994) and can be present in numbers of up to 100 000 individuals per square meter (Hopkin, 1997). Thus, their well-being plays an important role in ecosystem functioning.

In a Petri dish experiment without soil, Maaß et al. (2017) showed the passive transport of urea–formaldehyde particles $< 400\,\mu m$ and undefined PET fragments by two Collembola species (*Folsomia candida* and *Proisotoma minuta*) due to attachment, but they found no ingestion. Within a soil matrix, the trials carried out by Kim and An (2019) indicated a hindrance of collembolan migration by larger PS particles (44 ± 39, 282 ± 131 and $676 \pm 479\,\mu m$) at concentrations of $1000\,mg\,kg^{-1}$, corresponding to highly contaminated soils. In addition, they even found suppressed mobility due to the attachment of smaller PS microbeads (0.47–0.53 µm) at concentrations of $8\,mg\,kg^{-1}$ dry soil, which is equivalent to the values found in nature. Small particles ($< 50\,\mu m$) were moved, whereas larger particles were most likely cast off. When *F. candida* encounters two of its predators, the mites *Damaeus exspinosus* and *Hypoaspis aculeifer*, the dispersal of 80–250 µm PVC particles is enhanced, as shown by Zhu et al. (2018a) in a Petri dish experiment. Without proving ingestion or the minimal effective MP concentration, Zhu et al. (2018b) reported alteration of the gut microbiome and adverse effects on the growth and reproduction of *F. candida* by 80–250 µm PVC particles mixed in soil at concentrations of $1000\,mg\,kg^{-1}$ dry soil. These data were not considered robust (van Gestel and Selonen, 2018), but they concur with a later study that found inhibited reproduction at $\geq 1000\,mg\,kg^{-1}$ and avoidance behavior as well as microbiome alteration at $\geq 5000\,mg\,kg^{-1}$ (Ju et al., 2019). Such concentrations can occur in highly contaminated soils (Fuller and Gautam, 2016). However, documentation on the active uptake, gnawing and grinding of MPs by springtails proposed by Rillig (2012) is still lacking; furthermore, no studies on Diplura and Protura were found.

3.3 Annelida

Land-based Annelida comprise another large group of invertebrates. The Lumbricidae (earthworms) are a well-studied family (Darwin, 1881; Lavelle et al., 2006) that is represented in high abundance and diversity in many ecosystems all around the world (Phillips et al., 2019). Earthworms are often used as indicators of soil health (Fründ et al., 2011; Pulleman et al., 2012), as they are ecosystem engineers that, through their burrowing activity, influence various soil physical, chemical and biological processes (Jouquet et al., 2006; Lavelle et al., 2006).

The vast majority of studies on the influence of MPs on earthworms are performed using PE and the species *Lumbricus terrestris* or *Eisenia fetida*, but individual studies have also been carried out using *Aporrectodea rosea* (Boots et al., 2019) and *Eisenia andrei* (Rodriguez-Seijo et al., 2017) or the less common species *Metaphire californica* (H.-T. Wang et al., 2019). We found one field study on earthworms and MPs (Huerta Lwanga et al., 2017a) among many laboratory experiments with MPs mixed into soil volumes (concentrations ranging up to $20\,000\,mg\,kg^{-1}$ dry soil) or applied with litter on top of the soil surface (≤ 60 % w/w). The particles sizes were usually $< 1\,mm$ in diameter, although some were even up to $2\,cm \times 2\,cm$, and the duration of experiments was generally from 14 to 28 d, although a few lasted up to 60 d.

Table 3. Microplastic studies on Acari, Oniscidea (Onisc.), Tardigrada (T.) and Collembola. The abbreviations used in the table are as follows: fr refers to fragments, p refers to particles, mf refers to microfibers, mb refers to microbeads, ms refers to microspheres, [s] refers to semisubhydric, PHB refers to polyhydroxybutyrate, UF refers to urea–formaldehyde and NA denotes that information was not available. Concentrations refer to milligrams per kilogram dry soil unless indicated otherwise.

	Organism	Experimental environment	Plastic type	Aging	Coating	Additives	Shape	Size span (µm)	Concentrations	Exposure time	Passive transport	Active uptake	Bioaccumulation dynamics	Measured adverse effects	Reference
Acari	Diverse mites	Microcosm	PE	No	NA	NA	fr	< 4800	0–90 % v/v	16 d	NA	NA	NA	≥ 5 % v/v:	Stamatiadis and
			PS					> 2000	(manure)					abundance ↓	Dindal (1990)
	Hypoaspis aculeifer	Petri dish	PVC	NA	No	NA	p	80–250	5000 items	NA	Yes	NA	NA	NA	Zhu et al. (2018a)
	Damaeus exspinosus								per dish						
Onisc.	*Porcellio scaber*	Mesocosm	PHB	No	NA	NA	fr	4 cm^2	1 item per microcosm	14 d	NA	Yes	NA	Feeding ↓	Wood and Zimmer (2014)
	Porcellio scaber	Petri dish	PE	NA	NA	NA	fr	183 ± 93	0.4 % w/w	14 d	NA	Yes	NA	No	Kokalj et al. (2018)
								137 ± 51	(food)						
T.	Diverse tardigrades[s]	In situ	NA	NA	NA	NA	mf	NA	NA	NA	NA	No	NA	NA	Gusmão et al. (2016)
Collembola	*Folsomia candida*	Cup	UF,	NA	No	NA	p,fr	< 400	2.5–5 mg	NA	Yes	NA	NA	NA	Maaß et al. (2017)
	Proisotoma minuta		PET						per cup						
	Folsomia candida	Petri dish	PVC	NA	No	NA	p	80–250	5000 items per dish	NA	Yes	NA	NA	NA	Zhu et al. (2018a)
	Folsomia candida	Microcosm	PVC	NA	No	NA	p	80–250	1000	56 d	NA	NA	NA	Microbiome, growth ↓, reproduction ↓	Zhu et al. (2018b)
	Folsomia candida	Microcosm	PE	NA	No	NA	mb	< 500 0–10000 0–5000	0–10000 7 d 28 d	28 d	NA	NA	NA	≥ 5000: avoidance ≥ 1000: reproduction ↓ ≥ 5000: microbiome	Ju et al. (2019)
	Lobella sokamensis	Soil sample	PS	NA	Carboxyl	Fluorescence	mb	0.5	4–8	≤ 3 min	Yes	NA	NA	Avoidance, motivity ↓	Kim and An (2019)
			PE	No	NA	Fluorescence	ms	27–32	1000		Yes				
			PE	No	NA	Fluorescence	ms	250–300	1000		NA				
			PS	No	NA	No	fr	44 ± 39	1000		Yes				
			PS	No	NA	No	fr	282 ± 131	1000		NA				
			PS	No	NA	No	fr	676 ± 479	1000		NA				

The uptake of a broad size range of MPs by earthworms has been shown in studies based on particles in earthworm casts of *Lumbricus terrestris* (Huerta Lwanga et al., 2016; Cao et al., 2017; Hodson et al., 2017; Rillig et al., 2017; Prendergast-Miller et al., 2019; Yu et al., 2019; Huerta Lwanga et al., 2017a), *Eisenia fetida* (Rodríguez-Seijo et al., 2018; Chen et al., 2020; Wang et al., 2019b), *Eisenia andrei* (Rodriguez-Seijo et al., 2017) and *Metaphire californica* (H.-T. Wang et al., 2019). Zhang et al. (2018) showed that relatively large PE particles of 1.5 cm × 1.5 cm are not ingested by *Lumbricus terrestris*, but partial ingestion of such large particles of biodegradable MPs does take place after initial weathering in soil or in compost has occurred. In some laboratory experiments, MPs were found in the gut of dissected earthworms (Huerta Lwanga et al., 2016; Hodson et al., 2017; Rodriguez-Seijo et al., 2017), but the concentration of MPs in the gut was not significantly different between treatments nor significantly different from the bulk soil concentration; thus, there was no evidence of accumulation of MPs in the earthworm bodies (Hodson et al., 2017). Chen et al. (2020) assumed that an accumulation of MP takes place in *Eisenia fetida* based on an observed increase in MP concentrations in casts over the course of 4 weeks. Huerta Lwanga et al. (2017a) supposed an accumulation of MPs in the food chain as the concentration of MPs in chicken gizzards is strongly enhanced compared with that in the earthworm casts in the same experiments. However, it was mainly the amount of large particles, i.e., macroplastics, in the gizzards that was enhanced; thus, it seems more likely that the chickens directly fed on plastics, and an accumulation through the food chain cannot be proven given the current knowledge. Hence, this requires further investigation.

Several studies did not find significant negative effects of MPs on earthworms' avoidance behavior (Judy et al., 2019) nor on growth (Hodson et al., 2017; Rodriguez-Seijo et al., 2017; Judy et al., 2019; Wang et al., 2019b), mortality (Hodson et al., 2017; Rillig et al., 2017; Rodriguez-Seijo et al., 2017; Judy et al., 2019; Prendergast-Miller et al., 2019) or reproduction (Huerta Lwanga et al., 2016; Rodriguez-Seijo et al., 2017). However, other studies have shown adverse effects due to the uptake of MPs to different degrees and on different aspects of earthworms' fitness: reduced growth was shown by Cao et al. (2017) for *Eisenia Fetida*, and mortality increased at an exposure to MP concentrations of $\geq 10\,000\,\mathrm{mg\,kg^{-1}}$ dry soil. At lower concentrations, no significant effects were found. The growth of *Aporrectodea rosea* was also inhibited when exposed to biodegradable polylactic acid, which is a conventional high-density polyethylene (at $1000\,\mathrm{mg\,kg^{-1}}$ dry soil), and MP clothing fibers (at $10\,\mathrm{mg\,kg^{-1}}$ dry soil; Boots et al., 2019). Huerta Lwanga et al. (2016) showed a decrease in growth and increased mortality at concentrations of $\geq 28\,\%\ w/w$ in litter after 60 d, although after just 14 d no mortality occurred in these experiments.

In some studies, additional effects such as histopathological changes or stress biomarkers were measured. For *Eisenia fetida*, Chen et al. (2020) observed skin damage at MP concentrations of $1500\,\mathrm{mg\,kg^{-1}}$ in soil, measured an increase in catalase activity and malondialdehyde content at $1000\,\mathrm{mg\,kg^{-1}}$, and at $\geq 1000\,\mathrm{mg\,kg^{-1}}$ acetylcholine esterase was significantly stimulated. Wang et al. (2019b) tested *Eisenia fetida* and found that MPs only increased the catalase and peroxidase levels as well as the level of lipid peroxidation, whereas they decreased the activity of superoxide dismutase and glutathione S-transferase at an exposure of $200\,000\,\mathrm{mg\,kg^{-1}}$ dry soil for 14 d. No discernible influence was found at $100\,000\,\mathrm{mg\,kg^{-1}}$. However, Rodríguez-Seijo et al. (2018) also found a significant positive correlation between the MP concentration and different biomarker responses for *Eisenia fetida*: catalase, glutathione S-transferase, lactate dehydrogenase and thiobarbituric acid reactive substances. In addition, Rodriguez-Seijo et al. (2017) observed histological damage of the gut and the occurrence of inflammatory processes as well as an increase in stress response indicators associated with MP exposure in *Eisenia andrei*. For *Lumbricus terrestris*, Prendergast-Miller et al. (2019) showed an increase in metallothionein expression after exposure to an MP concentration of $\geq 1000\,\mathrm{mg\,kg^{-1}}$ dry soil and a decrease in heat shock protein 70 at a concentration of $\geq 10\,000\,\mathrm{mg\,kg^{-1}}$.

Due to the large differences in the experimental conditions, e.g., the size of the MPs, the addition of MPs to soil or to litter, the duration of experiments and the earthworm species, the current knowledge is not sufficient to detect the existence of a threshold MP size or concentration at which MPs become harmful for earthworms or how this threshold differs for different earthworms species and MP shapes. The results of Huerta Lwanga et al. (2016), who found no effects of MPs on earthworms after 14 d but a significant influence on growth and mortality after 60 d, indicate the importance of longer measurement periods. This is consistent with Pelosi et al. (2015), who concluded that the influence of pesticides on earthworm communities should be tested in long-term field experiments.

Earthworms' activity also increased the transport of MPs in soil columns to deeper soil layers (Rillig et al., 2017; Yu et al., 2019; Huerta Lwanga et al., 2017b); the smaller the MP, the stronger the transport. Particles are transported both actively – ingested and later cast out – and passively after attachment to the earthworm's body or by water flow through the biopores. As Huerta Lwanga et al. (2018) showed that the bacteria in the gut of *Lumbricus terrestris* can decompose MPs, it seems likely that particles taken up at the surface are egested as smaller particles in deeper layers.

MPs might well serve as a vector for contaminant transport to soil organisms. Although adsorption on plastics was seen to be lower than on the soil matrix, the desorption of Zn was observed to be higher in synthetic earthworm guts. However, there was no measurable negative effect of Zn or

PE on *Lumbricus terrestris* (Hodson et al., 2017). H.-T. Wang et al. (2019) studied the influence of MPs on arsenic uptake and the associated negative effects on *Metaphire californica* and concluded that MPs decreased the uptake of arsenic and reduced the influence of arsenic on the gut bacterial communities. Rodríguez-Seijo et al. (2019) showed altered enzyme activities and enhanced avoidance behavior in the face of low-density PE (LD-PE) pellets spiked with the insecticide chlorpyriphos. X. Yang et al. (2019) studied the influence of MPs on the transport of glyphosate; however, they mainly showed that the glyphosate transport was increased by earthworm activity, although the role of MPs in this transport could not be determined in their study. These studies show that MPs might have very different influences on the uptake and adverse effects of different pollutants on earthworms, and further investigation is needed in order to understand the influence of MPs on pollutant transport.

In contrast to the recently well-researched Lumbricidae, a near-relative, the family of Megascolecidae (giant earthworms), has not yet been mentioned in literature. Another branch within the Annelida, the small Enchytraeidae (potworms), have been shown to suffer adverse impacts on body weight and microbiome due to PS microspheres (0.05–0.1 µm) within their food source at concentrations of $\geq 10\,\%\ w/w$, but an unexpected increase in reproduction at $0.5\,\%\ w/w$ has also been reported (Zhu et al., 2018). Reproduction was reduced at abnormal concentrations of $90\,\mathrm{g\,kg^{-1}}$ dry soil of polyamide particles (13 to 150 µm) but not with PVC (Lahive et al., 2019).

The edaphon of semisubhydric soils is often treated as a marginal group between the respective areas of interest of soil and aquatic scientists. Although a highly diverse soil biocenosis is outside the focus of this paper, the benthos along seashores and fresh waters is also affected by MPs; therefore, it should briefly be mentioned by reviewing the lugworm *Arenicola marina*, a well examined deposit-feeder of the tidal flats. In situ, MP accumulates within its tissue and feces (Van Cauwenberghe et al., 2015). In laboratory experiments, PS particles ≥ 500 µm were avoided as a food source and were passively translocated within the sediment at concentrations of $\sim 2\,\mathrm{g\,kg^{-1}}$ (Gebhardt and Forster, 2018); however, these particles were measured within the feces at $\sim 74\,\mathrm{g\,kg^{-1}}$, effecting feeding activity and body weight but showing no influence on the survival rate (Besseling et al., 2012). PS microspheres ≤ 30 µm remained within the animal without any adverse effects regardless of particle size (Van Cauwenberghe et al., 2015). Other studies have found adverse effects on respiration, energy reserves, feeding, egestion and casting following the uptake of PVC particles ≤ 478 µm at different sediment concentrations of $> 2\,\mathrm{g\,kg^{-1}}$, although no effect on biomass or survival has been reported due to HD-PE (Wright et al., 2013; Green et al., 2016). There is further difficulty in distinguishing between the adverse effects of MPs and substances adsorbed on or leached from MPs (Besseling et al., 2012). When adding PCB-spiked PE to mud flat sediment at concentrations of up to $5000\,\mathrm{mg\,kg^{-1}}$ dry mass, there was no significant change in the survival rate or body weight. The decreased feeding activity and heap mass could be attributed to increasing plastic concentrations but not to enhanced PCB bioaccumulation via PE uptake (Besseling et al., 2017). However, all of these studies found adverse effects at MP concentrations that were orders of magnitude above natural values.

3.4 Further invertebrates

As part of the microfauna, the phylum Nematoda (nematodes or roundworms) is an ecologically important branch containing $> 25\,000$ species (Zhang, 2013) in freshwater, marine, endobiotic and soil habitats. Due to their diverse trophic interactions nematodes hold a central position in both bottom-up and top-down controlled food webs (Yeates, 2001; Ferris, 2010) and, thus, most likely the uptake and transfer of MPs.

Active feeding of adults and larvae of different species on 0.5–6 µm PS/latex microspheres (the size of their bacterial prey) has been proven by Nika et al. (2016) and Fueser et al. (2019). However, most MP experiments on Nematodes are based on the bacterial-feeding model organism *Caenorhabditis elegans*. Kiyama et al. (2012) showed the favored uptake of PS microspheres with sizes from 0.5 to 3 µm by adult and 0.5 µm by larval *C. elegans*. The ingestion of MPs decreased in the presence of bacteria as the natural food source.

When larval stages and adults ingested PS between 0.05 and 5 µm within an aqueous suspension or on agar plates, adverse effects such as oxidative stress, neurodegeneration, intestinal and DNA damage, or dysfunction in motility, growth, life span, defecation, reproduction or energy metabolism appeared over a wide spectrum of concentrations from $\geq 1\,\mathrm{\mu g\,L^{-1}}$ up to $\geq 86.3\,\mathrm{mg\,L^{-1}}$ (Zhao et al., 2017; Dong et al., 2018; Kim et al., 2019; Lei et al., 2018a, b; Qu et al., 2019a). These effects are not seen below $1\,\mathrm{\mu g\,L^{-1}}$ (Qu et al., 2019b), and they are enhanced due to amino modifications on microsphere surfaces (Qu et al., 2019c). The incubation on agar plates with PE, PP and PVC particles < 70 µm caused similar influences on survival, fertility, brood size and intestinal function (Lei et al., 2018b). Leachates from soils amended with $5\,\mathrm{mg\,kg^{-1}}$ dry soil of high-density PE (HD-PE) and PVC decreased reproduction in laboratory cultures, but there was no effect shown on survival after the application of PET (Judy et al., 2019). Furthermore, silica nanoparticles (0.05 µm) are not only taken up orally but also via the vulva and spermathecae, and they migrate into gonad cells (Scharf et al., 2013). This process was confirmed for PS nanoparticles with the potential of a transfer to the progeny (Zhao et al., 2017).

The clear adverse effects of these studies are limited in their representativity by a narrow restriction to liquid cultures and a single model organism. Broader studies like on prominent soil-dwelling nematodes such as *Acrobeloides buetschlii*

Table 4. Microplastic studies on Lumbricidae. The abbreviations used in this table are as follows: p refers to particles, ms refers to microspheres, b refers to beads, f refers to fibers, ms refers to microfibers, LD refers to low density, PLA refers to biodegradable polyactic acid, CPF refers to chlorpyrifos, PAHs refers to polycyclic aromatic hydrocarbons, PCBs refers to polychlorinated biphenyls and NA denotes that information was not available. Concentrations refer to milligrams per kilogram dry soil unless indicated otherwise.

Organism	Experimental environment	Plastic type	Aging	Coating	Additives	Shape	Size span (µm)	Concentrations	Exposure time	Passive transport	Active uptake	Bioaccumulation dynamics	Measured adverse effects	Reference
Lumbricidae														
Lumbricus terrestris	Mesocosm	PE	Washed (C_5H_{12}, C_8H_{18})	NA	NA	p	< 150	0–60 % w/w (litter)	14 d/60 d	Yes	Yes	NA	At 60 d, ≥ 28 % w/w: survival ↓, growth ↓	Huerta Lwanga et al. (2016)
Eisenia fetida	Glass beaker	PS	NA	NA	NA	ms	50–80	0–20 000	30 d	NA	Yes	NA	≥ 5000: survival ↓ ≥ 10 000: weight ↓	Cao et al. (2017)
Lumbricus terrestris	Bag	PE	NA	NA	NA	p	0.92 ± 1.09 mm^2	3500	28 d	NA	Yes	No	No	Hodson et al. (2017)
Lumbricus terrestris	Home yard	Diverse	Yes	NA	NA	NA	NA	0.87 ± 1.9 items g^{-1}	NA	NA	Yes	Concentration in chickens > in earthworms	NA	Huerta Lwanga et al. (2017a)
Lumbricus terrestris	Mesocosm	PE	Washed (C_5H_{12}, C_8H_{18})	NA	NA	p	< 150	0–60 % w/w (litter)	14 d	Yes	Yes	NA	NA	Huerta Lwanga et al. (2017b)
Lumbricus terrestris	Mesocosm	PE	NA	No	No	b	710–2800	750 µg on 2.5 kg soil	21 d	Yes	Yes	NA	No	Rillig et al. (2017)
Eisenia andrei	Mesocosm	LD-PE	NA	NA	NA	Pellets	250–1000	0–1000	28 d	NA	Yes	NA	≥ 62.5: intestinal damage	Rodriguez-Seijo et al. (2017)
Lumbricus terrestris (gut bacteria)	Mesocosm	PE	Washed (C_5H_{12}, C_8H_{18})	NA	NA	p	150	7 % w/w (litter)	60 d (earthworms)	NA	Yes	NA	NA	Huerta Lwanga et al. (2018)
	Glass bottle							10 000	21 d (bacteria)					
Eisenia fetida	Mesocosm	LD-PE	Washed (EtOH)	NA	NA	Pellets	250–1000	0–1000	28 d	NA	Yes	NA	≥ 125: altered enzyme activity	Rodriguez-Seijo et al. (2018)
Aporrectodea rosea	Mesocosm	PLA, PE	NA	NA	NA	p	NA	1000	30 d	NA	Yes	NA	Growth ↓	Boots et al. (2019)
		NA				f		10						
Eisenia fetida	Mesocosm	HD-PE, PET, PVC	No	NA	No	f	< 2000	Soil extract	48 h/56 d	NA	NA	NA	No	Judy et al. (2019)
Lumbricus terrestris	Bag	PE	NA	NA	NA	mf	∅40.7 ± 3.8 × 361.6 ± 387.0	0–10 000	35 d	NA	Yes	NA	≥ 1000: metallothionein expression ↑ ≥ 10 000: heat shock protein 70 ↓	Prendergast-Miller et al. (2019)
Eisenia fetida	Mesocosm	LD-PE	Washed (EtOH)	NA	CPF	Pellets	5000	40 items on 0.5 kg soil	14 d	NA	NA	NA	With CPF: altered enzyme activity,	Rodríguez-Seijo et al. (2019)
							250–1000	180–200 items on 0.5 kg soil					avoidance of MPs	
Metaphire californica	Mesocosm	PVC	NA	NA	Sodium arsenate	p	NA	2000	28 d	Yes	Yes	NA	Microbiome	H.-T. Wang et al. (2019)
Eisenia fetida	Glass beaker	PE	Washed	NA	PAHs, PCBs,	p	< 300	0–200 000	14 d	NA	Yes	NA	≥ 200 000:	Wang et al. (2019b)
		PS	(MetOH)		Nile red (NR)		< 250	0–100	28 d				altered enzyme activity	
Lumbricus terrestris	Mesocosm	PE	Washed (C_5H_{12}, C_8H_{18})	NA	Glyphosate	p	< 150	0–7 % w/w (litter)	14 d	NA	NA	NA	NA	X. Yang et al. (2019)
Lumbricus terrestris	Mesocosm	PE	NA	NA	NA	NA	< 1000	7 % w/w (litter)	14 d	Yes	Yes	NA	NA	Yu et al. (2019)
Lumbricus terrestris	Petri dish	PE and div.	Unweathered, field	NA	NA	p	1.5 cm × 1.5 cm	4 items per dish	14 d	Yes	No	NA	NA	Zhang et al. (2018)
	Mesocosm	biode-gradables	or compost				2 cm × 2 cm	10 items per dish	50 d		Yes			
Eisenia fetida	Bag	PE	Washed (EtOH)	NA	NA	p	< 400	0–1500	28 d	NA	Yes	Yes	Skin damage, ≥ 250 mg kg^{-1}: oxidative stress ≥ 1000 mg kg^{-1}: neurotoxicity ↑	Chen et al. (2020)

Table 5. Microplastic studies on Enchytraeidae (Enchyt.) and *Arenicola marina*. The abbreviations used in the table are as follows: mb refers to microbeads, p refers to particles, ms refers to microspheres, sed. refers to sediment, ^{s} refers to semisubhydric and NA denotes that information was not available. Concentrations refer to milligrams per kilogram dry soil in terrestrial soils and milligrams per kilogram dry sediment in semisubhydric soils unless indicated otherwise.

	Organism	Experimental environment	Plastic type	Aging	Coating	Additives	Shape	Size span (µm)	Concentrations	Exposure time	Passive transport	Active uptake	Bioaccumulation dynamics	Measured adverse effects	Reference
Enchyt.	*Enchytraeus crypticus*	Petri dish	PS	NA	NA	NA	mb	0.05–0.1	0–10 % w/w (food)	7 d	NA	Yes	NA	At 0.5 % w/w: reproduction ↑ ≥ 10 % w/w: microbiome, weight ↓	Zhu et al. (2018)
	Enchytraeus crypticus	Microcosm	PA	NA	NA	Fluorescence	p	13–150	20 000–120 000	20 h/21 d	NA	Yes	NA	≥ 90 000: reproduction ↓	Lahive et al. (2019)
			PVC			NA		106–150	90 000					No	
Arenicola	*Arenicola marina*^{s}	In situ	NA	NA	NA	NA	NA	NA	NA	NA	NA	Yes	1.2 ± 2.8 items g^{-1}	NA	Van Cauwenberghe et al. (2015)
		Liquid culture	PS	No	NA	NA	ms	10–90	10 000–50 000 items kg^{-1}	14 d	NA	Yes	10 µm: 9600± 1800 items kg^{-1} 30 µm:800± 700 items kg^{-1}	No	
	Arenicola marina^{s}	Mesocosm PA	PS	Yes	Biofilm	NA	p	500–1000	∼ 2000 ∼ 1000	106–240 d	Yes	No	NA	NA	Gebhardt and Forster (2018)
	Arenicola marina^{s}	Mesocosm	PS	NA	NA	NA	p	400–1300	0–74 000	28 d	NA	≥ 400 µm	No	≥ 74 000: feeding ↓, weight ↓	Besseling et al. (2012)
	Arenicola marina^{s}	Mesocosm	PVC	NA	NA	NA	p	9–478	0–20 000 mg kg^{-1} wet sediment	31 d	NA	NA	NA	> 2000: respiration ↓, casting ↓	Green et al. (2016)
			HD-PE					3–316						No	
	Arenicola marina^{s}	Mesocosm	PE	NA	PCBs	Fluorescence	mb	10–180	0–5000	28 d	NA	Yes	No	Feeding activity ↓, heap mass ↓	Besseling et al. (2017)
	Arenicola marina^{s}	Mesocosm	PVC	NA	NA	Not leaching	p	∼ 130	0–50 000	28 d	NA	NA	NA	≥ 10 000: energy reserves ↓ ≥ 50 000: feeding ↓, egestion ↓, casting ↓	Wright et al. (2013)

(Frey, 1971) are still lacking. When assuming in first proximity milligrams per liter solution is equal to milligrams per kilogram dry soil, the concentrations applied between 0.001 and 86.8 mg L^{-1} match lower levels of soil contamination.

Feeding studies on the phylum Rotifera with MPs are fully based on PS microbeads and model organisms of the planktonic genus *Brachionus*. However, these data can carefully be transferred to soil environments as soil rotifers are also aquatic organisms living in water-filled pores and water films. Different *Brachionus* sp. ingest microbeads $< 10\,\mu\text{m}$ with a strong preference for particles the size of their natural food source, namely bacteria and algae from 2 to 5 µm in diameter (Vadstein et al., 1993; Heerkloß and Hlawa, 1995; Baer et al., 2008; Jeong et al., 2016). The uptake appears to be selective, as fewer microbeads are incorporated compared with bacteria and algae (Vadstein et al., 1993). The egestion of particles $\leq 0.5\,\mu\text{m}$ is hindered compared with 6 µm particles (Jeong et al., 2016). In suspension, microbeads $\leq 0.5\,\mu\text{m}$ cause adverse effects on fertility and life span at $\geq 0.1\,\text{mg L}^{-1}$ as well as oxidative stress and inhibited growth at $\geq 10\,\text{mg L}^{-1}$ (Jeong et al., 2016; Sun et al., 2019).

Terrestrial mollusks comprise snails and slugs within the class of Gastropoda. These grazers feed on bacterial biofilms, fungi and plant tissue (Parkyn and Newell, 2013). Studies on terrestrial species are sparse, but data on the benthic *Littorina* sp. imply passive transport and nonselective MP uptake by feeding on surfaces with contaminated feces and mucus trails from other snails (Gutow et al., 2019). With focus on benthic snails, Imhof and Laforsch (2016) found no significant influence on the growth parameters and fertility of juvenile and adult *Potamopyrgus antipodarum* even when a food source with 70 % w/w of 5–600 µm sized fragments was given (a mixture of PA, PC, PET, PS and PVC). In contrast, adverse effects were found in recent work on the terrestrial snail *Achatina fulica*, which showed uptake and complete gastrointestinal passage within 48 h with partial degradation of PET fibers (approximately $1258 \times 76\,\mu\text{m}$), but reduced excretion and food intake as well as increased oxidative stress at concentrations of ≥ 0.01, ≥ 0.14 and $\geq 0.71\,\text{g kg}^{-1}$ dry soil, respectively (Song et al., 2019).

3.5 Vertebrates

Different taxa of the class of Amphibia have a predator function within the edaphic food web (e.g., preying on invertebrates; Hebrard et al., 1992). While no data on the reaction to soil MPs are available for the legless Gymnophiona nor for adults of the order Anura, sparse data on tadpoles of aquatic frogs suggest uptake followed by regular excretion of PS microspheres as shown for *Xenopus tropicalis* (Hu et al., 2016). Furthermore, no data exist on the Serpentes (snakes) and Anguidae families within the Reptilia class, which resides at the outer rim of the food web.

Within the broad field of Mammalia, studies on MP ingestion are sparse and focus on mice as a rodent model organism. Feeding of mice with PS microspheres from 1 to 14 µm at concentrations from 1.49×10^6 to 4.55×10^7 particles at a volume of $10\,\text{mL kg}^{-1}$ body weight for 4 weeks showed no adverse effects (Stock et al., 2019). In contrast, longer exposures (6 weeks) to lower particle concentrations with the same shape and size range changed the mouse microbiome and caused metabolic and intestinal dysfunction (Lu et al., 2018; Jin et al., 2019), which accompanies bioaccumulation within organs (Y.-F. Yang et al., 2019). These studies have regularly been conducted with passive feeding and exclude active foraging on perceptible plastic particles. However, the uptake via prey or feeding on contaminated roots and litter is highly probable. Further Rodentia – Cricetidae (hamsters, lemmings, voles), Bathyergidae (blesmols, mole-rats), Octodontidae as well as *spermophilus* (ground squirrels) and *marmota* (marmots) within the family of Sciuridae – have not yet been studied, as is the case for other mammalian (sub)orders like Chrysochloridae (golden moles), Cingulata (armadillos), Macroscelidea (elephant shrews), Notoryctemorphia and Peramelemorphia.

4 Synthesis

4.1 Summarized observations

Our systematic search comprised recent research on the interaction of soil organisms with MP as well as studies with a focus on feeding experiments, which were published far before people became aware of the issue that plastic poses. The numerous studies found that focused on the ingestion of MPs consistently showed active uptake by diverse soil organisms with few exceptions spread over the whole branch of invertebrates. In addition, studies on adverse effects caused by the intake of MP-contaminated food (e.g., uptake of food pellets by dung beetles) also implied the ingestion into the test organism. Distinct size preferences are observed in dung beetles, nematodes, rotifers and ants, with these organisms mainly ingesting particles that are small enough to enter the gastrointestinal tract. In contrast, active comminution by gnawing on larger particles has only been tested for a few taxa and has been confirmed for woodlice, termites, mealworms and earthworms (in the latter case, only after initial weathering).

After ingestion, MP is actively translocated until excretion or the death of the transporting organism, which has only been directly shown in experiments on earthworms. Passive transport by attachment, dragging and pushing has been investigated in a few experiments with earthworms, mites and springtails that partly worked without soil substrate and consistently showed positive results.

After exposure to MPs, a pattern of adverse effects can be seen: across various taxa, altered microbiomes, reduced motility, decreased body mass, lowered fertility and decreased life span as well as increased oxidative stress and metabolic malfunctioning occur in different combinations,

Table 6. Microplastic studies on nematodes. The abbreviations used in the table are as follows: ms refers to microspheres, fr refers to fragments, np refers to nanoparticles, mb refers to microbeads, ms refers to microspheres, ox. refers to oxidative and NA denotes that information was not available. Concentrations refer to milligrams per kilogram dry soil unless indicated otherwise.

	Organism	Experimental environment	Plastic type	Aging	Coating	Additives	Shape	Size span (µm)	Concentrations	Exposure time	Passive transport	Active uptake	Bioaccumulation dynamics	Measured adverse effects	Reference
Nematoda	*Caenorhabditis elegans*	Agar plate	PS	NA	Carboxyl	Fluorescence	ms	0.1–6.6	NA	0.5–2 h	NA	Yes	0.5–3 µm	NA	Kiyama et al. (2012)
					Sulfate										
					Amino										
	Caenorhabditis elegans	Liquid culture	PS	NA	Carboxyl	Fluorescence	ms	0.1	0.001–10 mg L^{-1}	4.5 d	NA	Yes	NA	≥ 0.01 mg L^{-1}: motivity ↓, growth ↓, defecation ↓, within gonads	Zhao et al. (2017)
	Caenorhabditis elegans	Liquid culture	PS	NA	$\zeta = -10$ mV	Fluorescence	ms	0.1	0.00001–0.001 mg L^{-1}	NA	NA	Yes	NA	≥ 0.001 mg L^{-1}: motivity ↓, ox. stress ↑	Dong et al. (2018)
	Caenorhabditis elegans	Liquid culture	PS	NA	NA	Preservatives, fluorescence	ms	0.05–0.2	0.001–86.8 mg L^{-1}	24 h	NA	Yes	NA	≥ 17.3 mg L^{-1}: motivity ↓, reproduction ↓ ≥ 86.3 mg L^{-1}: ox. stress ↑	Kim et al. (2019)
									17.3–86.8 mg L^{-1}					≥ 17.3 mg L^{-1}: metabolic dysfunction	
	Caenorhabditis elegans	Liquid culture	PS	NA	$\zeta = -10$ mV	Fluorescence	ms	0.1	0.001–1 mg L^{-1}	NA	NA	Yes	NA	≥ 1 mg L^{-1}: neurodegeneration ≥ 0.01 mg L^{-1}: motivity ↓	Qu et al. (2019a)
	Caenorhabditis elegans	Liquid culture	PS	NA	NA	NA	ms	0.1–5	1 mg L^{-1}	3 d	NA	Yes	NA	Motivity ↓, survival ↓, growth ↓, ox. stress ↑, neurotoxicity	Lei et al. (2018a)
	Caenorhabditis elegans	Agar plate	PE, PP, PVC, PS	No	NA	NA	fr, ms	0.1–200	0.5–10.0 mg m^{-2}	2 d	NA	Yes	NA	≥ 0.5 mg m^{-2}: survival ↓ at 5 mg m^{-2}: growth ↓, reproduction ↓, ox. stress ↑, intestinal damage	Lei et al. (2018b)
			PS	NA	NA	Fluorescence	ms	0.1–5						Mainly 1 µm: intestinal damage	
	Caenorhabditis elegans	Agar plate	Silica gel	NA	NA	NA	np	0.05	2500 mg L^{-1}	7 d	NA	Yes	NA	Within tissue and gonads	Scharf et al. (2013)
	Caenorhabditis elegans	Liquid culture	HD-PE, PET, PVC	No	NA	No	fr	< 2000	Soil extract	72 h	NA	NA	NA	Reproduction ↓	Judy et al. (2019)
	Caenorhabditis elegans	Agar plates	Latex	NA	NA	Fluorescence	mb	0.5	NA	30 min	NA	Yes	NA	NA	Nika et al. (2016)
	Caenorhabditis elegans	Liquid culture	PS	NA	NA	Fluorescence	ms	0.5–6	3 × 109–1010 items L^{-1} (∼ 0.2–1200 mg L^{-1})	4–73 h	NA	≤ 3 µm	NA	NA	Fueser et al. (2019)
	Panagrolaimus thienemanni											≤ 0.5 µm			
	Plectus acuminatus											≤ 1 µm			
	Poikilolaimus regenfussi											≤ 1 µm			
	Acrobeloides nanus											≤ 1 µm			
	Pristionchus pacificus											≤ 6 µm			
	Aphelenchoides parietinus											No			
	Caenorhabditis elegans	Liquid culture	PS	NA	NA	NA	ms	0.1	0.0001–0.001 mg L^{-1}	NA	NA	NA	NA	No	Qu et al. (2019b)
	Caenorhabditis elegans	Liquid culture	PS	NA	No	NA	ms	0.1	0.001–1 mg l^{-1}	NA	NA	Yes	NA	≥ 0.01 mg L^{-1}: reproduction ↓, DNA damage	Qu et al. (2019c)
					Amino									≥ 0.001 mg L^{-1}: reproduction ↓, DNA damage	

Table 7. Microplastic studies on Rotifera and Gastropoda. The abbreviations used in the table are as follows: ms refers to microspheres, mb refers to microbeads, fr refers to fragments, f refers to fibers, ox. refers to oxidative, pref. refers to preferential, [p] refers to planktic, [b] refers to benthic, PMMA refers to poly(methyl methacrylate) and NA denotes that information was not available. Concentrations refer to milligrams per kilogram dry soil unless indicated otherwise.

	Organism	Experimental environment	Plastic type	Aging	Coating	Additives	Shape	Size span (µm)	Concentrations	Exposure time	Passive transport	Active uptake	Bioaccumulation dynamics	Measured adverse effects	Reference
Rotifera	*Brachionus plicatilis*[p]	Liquid culture	PS	NA	Carboxyl	Fluorescence	ms	1.6–20	$5 \times 109\,\mu m^3\,L^{-1}$ ($\sim 5.25\,mg\,L^{-1}$)	35 min	NA	$\leq 10\,\mu m$	pref. 4.5 µm	NA	Baer et al. (2008)
	Brachionus plicatilis[p]	Liquid culture	Latex	NA	NA	Fluorescence	mb	0.3–3.1	3 × 107–7 ×108 items L^{-1} ($\sim$ 0.0004–11 $mg\,L^{-1}$)	20 min	NA	Yes	pref. ≥2 µm	NA	Vadstein et al. (1993)
	Brachionus koreanus[p]	Liquid culture	PS	No	NA	Fluorescence	mb	0.05–6	0–20 $mg\,L^{-1}$	1 d	NA	Yes	Egestion rate 0.05 µm < 0.5 µm < 6 µm	≤ 0.5 µm, ≥ 0.1 $mg\,L^{-1}$: reproduction ↓, survival ↓ ≤ 0.5 µm, 10 $mg\,L^{-1}$: oxidative stress ↑	Jeong et al. (2016)
	Brachionus plicatilis[p]	Liquid culture	PS	NA	NA	NA	mb	0.07–7	0–20 $mg\,L^{-1}$	NA	NA	Yes	NA	≤ 0.07 µm, ≥ 10 $mg\,L^{-1}$: reproduction ↓, growth ↓ ≤ 0.07 µm and ≥ 0.1 $mg\,L^{-1}$: survival ↓	Sun et al. (2019)
	Brachionus quadridentatus[p]	Liquid culture	PS	NA	NA	NA	ms	2–10	NA	8–10 d	NA	pref. 3–5 µm	NA	NA	Heerkloß and Hlawa (1995)
	Brachionus plicatilis[p]											pref. 2 µm			
Gastropoda	*Littorina littorea*[b]	Microcosm	PMMA	NA	NA	Fluorescence	fr	10–100	Increasing	16 h	NA	Yes	NA	NA	Gutow et al. (2019)
	Potamopyrgus antipodarum[b]	Aquarium	PET, PS, PVC, PA, PC	NA	NA	No	fr	5–600	0–70 % w/w (food)	≤ 141 d	NA	Yes	NA	No	Imhof and Laforsch (2016)
	Achatina fulica	Mesocosm	PET	NA	NA	No/stained	f	Approx. 1258 × 76	10–710	28 d	NA	Yes	Excretion after 48 h	≥ 140: food intake ↓ ≥ 10: excretion ↓ ≥ 710: ox. stress ↑, gastrointestinal damage	Song et al. (2019)

Table 8. Microplastic studies on Anura (An.) and Rodentia. The abbreviations used in the table are as follows: ms refers to microspheres, [a] refers to aquatic and NA denotes that information was not available.

	Organism	Experimental environment	Plastic type	Aging	Coating	Additives	Shape	Size span (µm)	Concentrations	Exposure time	Passive transport	Active uptake	Bioaccumulation dynamics	Measured adverse effects	Reference
An.	*Xenopus tropicalis*[a]	Petri dish	PS	NA	NA	Fluorescence	ms	1–10	100–108 items L^{-1} (55×10^{-9}–55 mg L^{-1})	48 h	NA	Yes	Egestion within days	NA	Hu et al. (2016)
Rodentia	Transgenic mice	In vivo	PS	NA	Carboxyl	Fluorescence	ms	1	4.55 × 107 items per mouse (0.025 mg per mouse)	28 d	NA	Yes	NA	No	Stock et al. (2019)
					Sulfate			4	4.55 × 107 items per mouse (1.6 mg per mouse)						
					Sulfate			10	1.49 × 106 items per mouse (0.8 mg per mouse)						
	Mice	In vivo	PS	NA	NA	Fluorescence	ms	5	0.1–1 mg L^{-1} (food)	42 d	NA	Yes	NA	≥ 0.1 mg L^{-1}: microbiome, metabolic dysfunction	Jin et al. (2019)
	Mice	In vivo	PS	NA	NA	NA	ms	0.5–50	0.1–1 mg L^{-1} (food)	35 d	NA	NA	NA	≥ 0.1 mg L^{-1}: microbiome, metabolic dysfunction ≥ 1 mg L^{-1}: body weight ↓	Lu et al. (2018)
	Mus musculus	In vivo	PS	NA	NA	Fluorescence	ms	5–20	200 mg L^{-1} (food)	28 d	NA	Yes	8 ± 5 and 0.71 ± 0.14 mg kg^{-1} body weight	NA	Y.-F. Yang et al. (2019)

mainly due to micrometer-sized MPs in and above the whole known natural range of concentrations. For some taxa such as Nematodes, Gastropoda and Rotifera these effects appear at natural and increased MP concentrations ($< 100\,\mathrm{mg\,kg^{-1}}$ dry soil); for Collembola and Lumbricidae, these effects are found at concentrations such as those seen at highly contaminated sites ($\geq 1000\,\mathrm{mg\,kg^{-1}}$ dry soil); and for Enchytraeidae, *Arenicola marina* and in further experiments with earthworms impacts are seen at implausibly high values. The data show a tendency for effects to occur at lower concentrations, when the added particles are smaller. Small-sized particles also provide the highest surface to volume ratio and, thus, the highest reactive surface per weight.

Most studies work with defined increasing MP concentrations and particle sizes in soil substrates and food sources, which can be used to determine relationships between environmental concentrations and adverse effects. However, the lack of information about intake rates, grades of accumulation and effective prey–predator transfer leads to a gap within the chain of explanation regarding the toxic effects on the soil organisms. In some experiments, the intestinal passage of MPs and sizes preferably retained within the gut have been shown, but no experiments have been able to demonstrate quantitative bioaccumulation. In contrast, quantification of the retained and egested MP particle size fractions might be biased due to gnawing and intestinal comminution as shown for woodlice, termites, mealworms, snails and earthworms.

In order to improve our understanding of processes underlying the adverse effects of MPs on soil organisms, data on ingestion rates, dwell times, biodegradation and egestion rates are important factors, e.g., to reveal bioaccumulation dynamics. However, few data exist on biodegradation (mealworms, snails and earthworms), egestion (rotifers, frogs, snails and earthworms) and remaining concentrations in the body (lugworm, mice and earthworms).

4.2 Limitations of previous studies

The available studies worked with items within the full size span of microplastics and nanoplastics ($\leq 5000\,\mu\mathrm{m}$). Approximately 72 % of the experiments used microplastic (0.1–5000 µm), 6 % used nanoplastic ($< 0.1\,\mu\mathrm{m}$), 10 % included macroplastic ($> 5000\,\mu\mathrm{m}$) and 12 % used microplastic of undefined size. When MP $\geq 50\,\mu\mathrm{m}$ was applied, mainly particles and fragments made of PE and PVC were used, whereas PS/latex microspheres were mainly applied for sizes $\leq 10\,\mu\mathrm{m}$ (Table 1). The latter are readily available, highly standardized and are mostly used with fluorescent dyes and without additional functional groups, carboxylated, or, more rarely, with amino or sulfate groups. However, there are indications that the spectrum of particle type and shape used in experiments does not correspond to the properties of particles in soils. At different natural as well as agriculturally and industrially contaminated terrestrial and semisubhydric sites, fibers and fragments of PE and PP, mostly $\leq 100\,\mu\mathrm{m}$, were found to be much more abundant than PVC, PET and PS items (Claessens et al., 2011; Vianello et al., 2013; Nor and Obbard, 2014; Naji et al., 2017; Zhang and Liu, 2018; J. Li et al., 2018). This is probably caused by high loads of MP fibers in discharged waste water and sewage sludge, which are used at agricultural sites worldwide (Mahon et al., 2016; X. Li et al., 2018). It is likely that shape plays an important role in the ingestion of MP items. Unfortunately, we did not find any studies that have carried out a complete classification of sampling sites according to plastic origin, size and type, which could help to evaluate the differences between former experimental and natural plastic composition to achieve the most realistic experimental conditions. Moreover, the limited knowledge on the size distribution of MPs in soils further complicates the determination of realistic concentrations for the addition of a certain particle size spectrum. All of the studies reviewed either arbitrarily set their applied concentrations or had to base them on measurements of total specific MP masses, regardless of how much of this mass is within the tested size range. This may lead to a false estimation of total adverse MP concentrations.

In contrast to particle type and shape, the documentation of chemical properties of MP samples in most of these studies is fragmentary. Some experiments explicitly mentioned that the added plastic was unweathered, whereas most studies lack information about the degree of aging, thereby implying that unweathered items were used. Only a few experiments involved the aging of MPs, but there was also no comparison to the results of natural weathering (Tsunoda et al., 2010; Gebhardt and Forster, 2018). This is in conflict with natural conditions, as plastic that remains within the soil after littering, sewage sludge application or plastic mulching shows signs of weathering, e.g., modified carbonyl indices (Andrady, 2017), whereas unweathered soil MPs might be rare. In addition, Zhang et al. (2018) showed that earthworms only actively comminute weathered bioplastics. In experiments using PS microspheres, carboxylation is often used to imitate a reduced hydrophobicity due to weathering. However, according to manufacturer information, microplastics only have a small influence on hydrophobicity.

Weathering of MP surfaces within soils comes along with biofilm growth and the adsorption of organic molecules, which could potentially affect the attractiveness or toxicity for grazers and other organisms. Such coatings were only applied in a few cases (Besseling et al., 2017; Angotti et al., 2018; Gebhardt and Forster, 2018), but they were not documented in most studies. Similarly, the type and concentration of additives such as flame retardants, antioxidants or stabilizers often remained undocumented, with the exception of fluorescent dyes, which are well mentioned. The release of additives can have a harmful effect on the test organism, as shown for aquatic environments (e Silva et al., 2016). Some studies on the ingestion of MPs by the soil mesofauna indicate that the diameter of the gastrointestinal tract is a useful upper size limit for added particles, as far as the organism is unable to crush them (Heerkloß and Hlawa, 1995; Holter, 2000; Holter et al., 2002; Holter and Scholtz, 2005; Baer et al., 2008; Fueser et al., 2019). However, using only ingestible particle sizes in their natural concentrations neglects the adverse effects of plastic leachates, which can also get into the soil solution and onto the mineral phase from larger particles and, thus, affect soil life.

The incubation conditions differ considerably in terms of habitats and the duration of exposure. In most studies, the exposure ranges from a few minutes to a few days in experiments with microfauna and small mesofauna and hours to several weeks in experiments with large mesofauna and macrofauna and is mainly based on excretion or reproductive cycles. Long-term studies, which are indeed difficult to carry out in mesocosms, practically do not exist. However, certain adverse effects might only establish themselves after long-term trials, as was shown for the influence of pesticides (Pelosi et al., 2015).

Some experiments were carried out in soil-free test environments, such as liquid cultures or Petri dishes with nutrient solutions or a specific food source (nematodes, rotifers, mice). Therefore, motivity is less restricted and feeding behavior can be altered compared with cultivation within soil environments. For example, the ingestion of MPs by nematodes decreases in the presence of an alternative and more natural food source, like bacteria, which can significantly reduce the bioaccumulation and, thus, the effective toxicity (Kiyama et al., 2012). This can lead to less consumption of MP in soil environments and an overestimation of the toxicity in liquid culture experiments. Moreover, all laboratory feeding experiments were carried out using only one species. Thus, the complexity of the food web in soils is excluded, and the potential accumulation from prey to predators remains unexplored.

4.3 Directions for future research

Most studies reviewed in this work have a pioneering role in MP research and, thus, are subject to some experimental limitations caused by an early state of knowledge. The adverse effects recently found are alarming, but they must be considered within the framework of the abovementioned restrictions. We propose the following points as part of a modus operandi for future MP research.

In past studies, particular adverse effects of MPs have only been measured for certain sizes, shapes, coatings, leachates or adsorbed substances (Tables 2–8). Experimental concentrations have been assumed randomly or derived from cumulative concentrations of one or more MP types measured in natural soils (approximately 1 to some 1000 $mg\,kg^{-1}$ dry soil), regardless of size. In future experiments, the spectrum of concentrations used should be adapted to the quantities of the size spectrum that occurs within the soil. For upcoming studies on mixed contaminations, we recommend an evaluation of the overall adverse effects of PE, PP, PVC, PET, PU and PS to certain test organisms using typical MP-specific concentration ranges, sizes and shape distributions in natural soils or food samples. This requires well-structured data on the appropriate MP type, shape and size for different soils in differently contaminated areas.

Experiments on adverse effects should be applied within soil matrices to allow the interplay of plastic, natural organic and mineral matter. MPs should be weathered, as plastic in soils undergo broad environmental aging. Therefore, pre-weathering of MPs should not only be performed in climate chambers (e.g., following DIN EN ISO 4892-2/3) but should also include subsequent leaching and equilibration of additives or coatings within the soil matrix before the main experiment. Furthermore, the experimental design may consider coatings with biofilms or attractants and even particle color to regulate the preference of the test organisms.

Most detailed information about ingestion is available for dung beetles, nematodes and earthworms, and most data on adverse effects has been gathered for nematodes, earthworms, lugworms and Collembola. Future experiments should focus on a larger variety of ecologically relevant taxa like Coleoptera, Formicidae, Acari, Oniscidea, Collembola, Lumbricidae, Enchytraeidae, Nematoda and Gastropoda. It is recommended that these studies focus on uptake, accumulation and key adverse effects such as survival rate, motility, growth and fertility as well as on the stability of the intestinal microbiome. Further studies with more than one test organism are important to foster our understanding of MPs within certain food chains. Moreover, long-term experiments might reveal adverse effects that evolve slowly within populations. This may enable the assessment of the distribution and effects of MPs within the food web and the resulting long-term impact on soil ecosystems.

5 Conclusion

Our review of 77 studies on the impact of MPs on the soil fauna shows a considerable diversity and distribution of adverse effects within the soil tree of life. However, these effects have to be considered carefully, as many experiments did not use plastic matching the properties of plastic found within natural soils and only observed adverse effects at concentrations mirroring those of highly contaminated soils (or concentrations above these levels). To elucidate effective concentrations and properties for short- and long-term effects on soil faunal health, the most exact reproduction of plastic properties within the soil matrix and natural living conditions of the test organisms is necessary as well as a better knowledge of common concentrations and size distributions of soil MP. Therefore, for future experiments, we recommend the selection of compositions of types, shapes, sizes, concentrations, grades of weathering, leachability and coating with biofilms and other organic matter that match those expected in the habitat to be examined. Furthermore, coming studies should include long-term exposure and food chain experiments to get a better look at the effect of even smaller MP concentrations and their enrichment within the food web. This may provide a more effective way of assessing the impact of global MP contamination on factors such as soil biodiversity, soil carbon cycles and soil quality.

Data availability. All of the data are published within this paper and in the Supplement.

Supplement. The supplement related to this article is available online at: https://doi.org/10.5194/soil-6-245-2020-supplement.

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