# Microplastics and Their Effects on Soil Function as a Life-Supporting System

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## Contents



**Abstract** Particles play important roles in terrestrial systems, where the natural soil environment provides a complex habitat in which the three-dimensional organization of mineral and organic matter is combined to a diverse array of water levels, microscopic life forms, and their metabolites. Soils are the foundation for most land-based life and terrestrial ecosystem services that benefit humans. When plastics

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arrive at the soil, their nonnatural structure, distinct chemical composition, and unique surface properties trigger a series of abrupt environmental changes in the soil. Indeed, the current evidence suggests changes in the fundamental physical, chemical, and microbiological properties of the soils. Consequently, water and other biogeochemical cycles, as well as plant performance and animal health, can be affected. In this chapter, we present the recent advances in understanding how microplastics can change elementary properties of soil systems, such as soil aggregation and structure. This is discussed jointly with the linked effects in the microbial activity and function. Then, we address the recent studies regarding the effects of micro- and nanoplastics on plants and animals. Finally, we elaborate the properties of the various types of microplastics, soil processes, and soil organisms that are probably influencing the observed effects. We conclude by highlighting that current scientific information is not enough to devise solid risk assessments on microplastics in soils and suggest research directions to fulfill this gap.

**Keywords** Biogeochemistry, Environmental change, Microbiome, Plants, Soil fauna

## 1 Introduction

Natural particles play important roles in terrestrial systems [1]. The very complex interaction of these particles with water, air, and natural biogeochemical cycles is what makes possible the provision of many environmental services that sustain our leisure, our food, and our health [2]. Take the example of the soil system. Soils are a collection of natural particles of various sizes and from mineral and organic origins that trap and interact with gases, liquids, and organisms. Thus, soil health is fundamental for proper function of processes affecting agriculture, global climate, or even things seemingly not related such as urban resilience to flooding [3].

We can describe the natural soil environment as a complex and highly heterogeneous habitat in which the three-dimensional organization of mineral and organic particles is combined to a diverse array of water levels, microscopic life forms, and their metabolites [3]. This structured and multifaceted physical, chemical, and biological entity is referred to as the soil biophysical environment, and it has evolved over millions of years to form the life support system touching all living things on land from the smallest microbes to the largest elephants. When water and air are combined with the inorganic matter (clay, sand, silt, minerals) and organic matter (decaying and decayed plant and animal material) within soils, the needs of the diverse array of micro-, meso-, and macrofauna can be provided. Thus, the dependency on soils is the foundation of all terrestrial ecosystems, and it is of the highest relevance to the trophic food webs as it supports directly and indirectly the incredible diversity in forms of life seen in the world [3].

While you are reading these paragraphs, innumerable physical and chemical interactions are occurring between soil particles and other soil particles, between soil particles and water, and between soil particles and air. These interactions critically affect key parts of ecosystems [3]. One example is the rhizosphere, the portion of soil that directly affects and is affected by the roots of plants. The organic material in soil is full of essential nutrients which are inaccessible to plants and must first be mineralized by microorganisms [4]. Via mineralization, complex organic molecules are transformed into inorganic nutrients which can dissociate in a water solution into electrically charged ions. These ions are then available for uptake by plant roots either directly from the soil solution or from soil colloid surfaces. Negatively charged ions (anions) such as nitrate ($NO^{3-}$) and sulfate ($SO_4^{2-}$) are mostly found in the aqueous phase of the soil, the soil solution. On the other hand, inorganic components of soil such as fragments of rock and small minerals present in a water-fine particle mixture (soil colloids) attract positively charged ions (cations) such as ammonium ($NH_4^+$) and magnesium ($Mg^{2+}$). Plant roots are in intimate contact with the soil solutions and the soil colloids. Water and ions are exchanged along electrochemical gradients between the soil solution and colloids, the solution and roots, and roots and colloids in all directions [5]. Thus, all components of the soil system are involved in ion and water dances that provide plants with the necessary building blocks to perform photosynthesis.

Other physical properties of soil such as bulk density, soil moisture, and soil structural stability affect the habitability of soils by influencing water retention, aeration, and aggregation [6]. These interactions are paramount to the health of soil systems and the soil biophysical environment and, therefore, to the terrestrial components of the Earth's biosphere. It is within this context that a nonnatural foreign material like microplastics (MPs) might represent potential risks of altering the still poorly understood interactions between particles, water, chemicals, and microbes in the soil system [7].

Plastic litter arrives to soil as meso- and macroplastics (as discussed in Part 2, Chaps. 3–10). These large plastics are slowly broken down into microplastics (<5 mm) and eventually nanoplastics (<100 nm), and accompanying their decrease in size, there is an exponential increase in number, surface area [8], and likely bioavailability. The decrease in size also allows for easier integration into soil [9]. It has been shown that earthworms ingest microplastics and carry on transferring them vertically and horizontally throughout the soil column via cast excretions [10, 11]. It has been also demonstrated that collembolans can interact with micro- [12] and nanoplastic particles with consequences to their biology [13]. Thus, it is logical to assume that other soil macrofauna such as ants and termites as well as soil-dwelling animals such as moles are significant potential incorporators of plastics into soils [7]. A more well-documented integration of plastics into the rhizosphere has been taking place due to the decades-old practice of fertilizing agricultural lands with dried and pelleted sludge from human sewage [14]. This sludge, heavily laden with micro- and nanoplastics, is applied season after season directly to the crops [15]. The common practice of mass tillage further incorporates such microplastic particles into the soil column where they have the potential to interact with soil components and are accessible to microbes and plant roots [9].

The organisms and the soils themselves change and evolve over the geological time, so that abrupt changes to soil composition on a global scale are rare. Nonetheless, plastics might be among the most sudden, pervasive, and longest-lasting forms of global anthropogenic pollution affecting soil and environmental systems more broadly. Plastics and MPs are dispersed by numerous processes in litho-, hydro-, and atmosphere and currently found in every habited and uninhabited continent on our planet. MPs swept up by wind currents are scattered down by rain or snow reaching all corners of the globe including both the Arctic Circle and Antarctica. In fact, there is a growing concern that MPs might constitute a driver of global change in terrestrial systems [7, 16]. In this chapter, we will explore some of the observed impacts of microplastic contamination of soils as a life support system and their effects for fundamental functions of the terrestrial ecosystem. We will discuss the known effects that occur to terrestrial animals when they ingest plastic particles as analogies to the aquatic environment. Nevertheless, we will mostly focus on organisms, traits, and functions that are specific to the soil and terrestrial realm, such as rhizosphere effects. In the end, some recommendations and future directions will be given.

## 2 The Evidence for Impacts of Microplastics on the Soil Environment

The biopersistent composition of plastics summed to their structural differences to natural matter and to the inherent association of this material with human activities yields the possibility of a myriad of hazards to the soil environment [7]. These hazards might entail relevant risks since some authors have found levels of MPs in weight of top soil up to 7% in contaminated areas [17], and counting of particles suggests that concentrations up to 40,000 microplastic particles per Kg of soils [18] might be environmentally realistic. Within soils, MPs might persist for more than 100 years due to low light and oxygen conditions [19]. Therefore, soil MPs will certainly interact with soil fauna and flora, potentially changing their behavior, their fitness, and consequently the biophysical environment and its function [7].

In fact, both conceptual and empirical evidence suggest that MPs act as drivers of environmental change in the soil environment. From passive carriers of pathogenic microorganisms to active transformers of the way soil functions, this section deals with how soil MPs are shown to change the way microbes, plants, and animals interact with their habitat.

### 2.1 Microbes and Microplastics in Soil

There are multiple mechanisms proposed as means of MPs affecting soil microbial communities, some of which are similar to the effects in aquatic microbiomes, while others might be specific to the soil habitat. For instance, within wastewater treatment plants, MPs are shown to be enriched with both pathogenic and opportunistic organisms [20]. Empirical data for the microbial communities in those particles suggests that even after environmental release, microbes in the microplastic surfaces contained higher levels of antibiotic resistance genes and other markers of microbial horizontal gene transfer [21]. If the sewage sludge is employed as a soil amendment, microplastic particles might enter soil systems and subsequently disperse such genetically diverse microbes within those systems [7]. Moreover, it is now established that, in aquatic systems, microplastic particles are surrounded by an ecocorona consisting of many proteins, organic compounds, and microbes [22]. This is relevant to soils because the majority of soil microorganisms are essentially aquatic organisms, i.e., thriving in the interstitial water on or between soil particles, known as soil pore water [23]. Thus, if MPs surface properties distinct from those of natural organic and mineral particles, it could act as a selective force to diversity of soil microbiomes [7]. The effects of MPs as vectors of pathogenic microbes or as active selective surfaces to terrestrial microbiomes remain largely unexplored and represent relevant areas for future research.

Some of the first experimental data suggesting MPs' impact on microbial function was the work from Liu et al. [24]. These authors investigated the effects of high levels of polypropylene contamination (7 and 28% of soil weight) on the cycling of soil dissolved organic matter, dissolved phosphorus, and microbial activity [24]. Their conclusion was that microplastic addition affected the decomposition of organic matter, microbial enzymatic activities, and levels of nutrients [24]. This study provided unprecedented and ecologically meaningful evidence of microplastic effects on microbial function. However, the mechanistic nature could not be formulated as information on particle size distribution and soil chemistry was missing. The only information about the polypropylene known is that particles were smaller than 180 μm, which is not accurate enough to delineate possible effects in soils, since the mode of impacts of microplastic particles is a mixture of physical and chemical effects that vary with the particle size [7, 25].

In this context, the work published by Machado et al. [26] provided additional insights into the changes in microbial function as well as the possible mechanisms underlying such as alterations of bulk density of soils. Machado et al. [26] exposed a sandy loam soil to four types of MPs varying in physical and chemical properties, namely, polyester and polyacrylic fibers, polyamide beads, and polyethylene fragments. These MPs were added to the soil at four levels of contamination (up to 2% of soil weight) and incubated under natural conditions for several weeks. Thus, these authors could associate the various changes in fundamental properties of the soils (e.g., soil bulk density, water holding capacity, and soil aggregation) with the changes in the microbial activity. The study also demonstrated that the effects were highly dependent on the particle type and possibly not monotonically varying with concentration [26]. This implies that a simultaneous quantification of microplastic chemistry, structure, size, and concentration is essential for the assessment of the combination of impacts of various particles in the soil microbiome [26]. In other words, effects cannot be simply assigned to unspecific "microplastic" concentrations, since specific particle properties (linear vs nonlinear, size distributions, polymer, etc.) seem to matter [27]. Despite these many idiosyncrasies, their study also revealed that for most of the proxies for health of the soil biophysical environment, microplastic fibers were the ones eliciting the strongest effects. The most remarkable effect on soil microorganisms triggered by MPs was a change in microbial metabolic activity that was linked to functional changes [26]. In other words, soil microbes were not only active at different levels in soils treated with MPs. They were also impacting soil aggregation and structure in a distinct way compared to the controls.

In a follow-up experiment, Machado et al. [28] investigated the potential of MPs to trigger changes in the soil environment considering six different types of MPs added to bulk soil and rhizosphere. They reported that a broad suite of parameters of soil physical quality were affected with consequences for water dynamics. For instance, soil bulk density was decreased by the studied high-density polyethylene, polyester, polyethylene terephthalate, polypropylene, and polystyrene particles when plants were not present [28]. Also the soil structure and aggregation were affected by all microplastic treatments tested, with the intensity and direction of effects depending on the microplastic type, aggregate size fraction, and plant presence. As a result of distinct structure and density (i.e., change in total pore space), the interaction of soils with water was affected. Evapotranspiration and soil moisture were strongly affected by the presence of MPs. As an example, evaporation was increased by $\sim$35% by polyamide beads and $\sim$50% by polyester fibers, and smaller increases were triggered by high-density polyethylene, polyethylene terephthalate, and polystyrene fragments [28]. The observed increases in evaporation were smaller than increases in water holding capacity, which resulted in soils containing MPs retaining higher water availability. In turn, the alterations caused by MPs on structure and soil water cycling also resulted in significant changes, in general microbial metabolic activity by polyamide beads, high-density polyethylene fragments, and polyester fibers. Interestingly, microbial activity in the rhizosphere was decreased by polyamide beads and high-density polyethylene and polyethylene terephthalate fragments. Moreover, functional changes on the bulk soil and rhizosphere microbiomes were also observed, including alterations in the colonization of the roots of spring onions (*Allium fistulosum*) by arbuscular mycorrhizal fungi (AMF) (polyester fibers at 0.2% of soil weight increased eightfold the AMF presence) [28]. In fact, in addition to changes in the infection with AMF, the economics of this symbiosis was also distinct, which was evidenced by the shifts in the proportion of arbuscular, vesicular, and other AMF structures responsible for exchange and storage of metabolites. Other non-AMF infections were also increased in soils with microplastic polyester fibers.

This potential of MPs to affect the general metabolic rate and function of the entire soil microbial communities is of great relevance [26]. Soil microbiomes are responsible for important biogeochemical cycles that affect human and environmental health [29, 30]. For instance, if MPs would negatively impact denitrification rates, it could cause problems similar to mineral fertilizers [31]. Nitrate is mobile and transferable to aquatic systems, and its accumulation causes eutrophication of surface waters and compromising aquifer potability. In fact, impacts in surface and ground water have been noticed as adverse consequences of alterations in the activity of nitrogen-cycling bacteria [32]. Moreover, the altered microbial activities observed by Machado et al. [26, 28] and Liu et al. [24] may reflect altered microbial biodiversity, while the changes in the association between microbial activity and soil aggregation [26] might represent either a shift in microbial community or a modification in the decay of soil organic matter (e.g., preferential electron donor). Indeed, feedback loops in changes of soil microbial communities and the fate of organic matter are conceivable. Moreover, the physical properties altered by MPs in Machado et al. [7, 26, 28] are known to affect microbial communities. For instance, polyester fibers can decrease water-stable aggregates, which are considered potential hotspots for microbial evolutionary processes within the soil. Thus, decreases in soil aggregation may cause habitat loss for soil microfauna, e.g., fewer surfaces for colonization or for "hiding" from predators.

It is clear that such impacts of MPs will depend on behavioral, biochemical, and physical processes taking place on the micro- and nanoscale in the soil environment, which are difficult to predict. Nevertheless, it is a vital imperative to obtain a solid understanding of the potential implications of introducing massive quantities of plastics into global soils. There are biogeochemical, ecotoxicological, and biodiversity threats associated with impacts on soil microbiomes where even small changes could have ecological and economic consequences relevant broadly for terrestrial agricultural and natural ecosystems [29]. Therefore, further studies should clarify the mechanisms of the biodiversity and functional responses of soil microbes to changes in biophysical conditions related to MPs.

## *2.2 Plants and Microplastics in Soil*

The above-discussed effects on soil physical properties and soil microbiota suggest potential impacts of MPs on the performance of terrestrial plants [26]. There is a lack of experimental research in this area. Nevertheless, the first body of evidence sheds light into several possibly ways that MPs interact with plants [28]. One of the first studies on the interactions of MPs and plants arose from the work of Liebezeit and Liebezeit [33, 34] when it was identified that commercially available honey (both industrial and artisanal) contained MPs [34]. When tracking the sources of this contamination, these authors found that various microplastic particles were broadly present in the inflorescences of diverse plant species [33]. The bees were carrying MPs from the flowers to beehives and then to the produced honey [33]. This might imply interference on plant-pollinator relationships. Perhaps more interestingly, Sanders and Lord [35] had detected that when 6 μm microplastic particles were introduced into transmitting tracts of styles of inflorescences of various species, these particles were actively translocated by the plants to the ovary. Thus, plastic beads compatible with sizes of pollen can travel to the ovules as do pollen tubes [7]. Environmental effects of the microplastic presence in plant inflorescences have not been demonstrated. However, other ways of the interaction plant-microplastics have been observed to cause significant effects.

The research from Qi et al. [36] was possibly the first experimental investigation of effects of macro- and microplastic residues from mulch film on the growth of wheat (*Triticum aestivum*). In this study, they reported responses of a plant-soil system exposed in a greenhouse at 1% of a sandy soil weight in low-density polyethylene or a biobased plastic (starch-based biodegradable film consisting of 37.1% pullulan, 44.6% polyethylene terephthalate, and 18.3% polybutylene terephthalate). Both macro- and microplastic films affected above- and belowground biomass of the wheat [36]. According to the authors, such alterations occurred during vegetative and reproductive growth. They also observed that the type of plastic strongly influenced the responses, with the bioplastics having the most pronounced effects.

The most comprehensive study on the effects of MPs to a single plant species currently available is from Machado et al. [28]. They contaminated a soil with one of six different types of MPs, including fibers, beads, and fragments of distinct sizes and chemistries. After a period of acclimation of soil microbiomes to the presence of MPs, they planted the spring onion seedlings. MPs affected root and leave traits as well as total biomass and several morpho-physiological features of exposed plants [28]. For instance, polyester fibers and fragments of polystyrene, high-density polyethylene, polyethylene terephthalate, and polypropylene increased root biomass. And all the tested MPs increased root length and surface area but decreased root average diameter [28]. The effects are not always uniform, however. Polyamide beads decreased the ratio between roots and leaf dry biomass, while polyester fibers and the microplastic fragments significantly increased this ratio. Polyester fibers triggered the strongest effects on the interaction of the spring onions' roots and the surrounding microbial communities. In terms of leaf traits, polyamide beads increased onion bulb biomass, while polyester fibers nearly doubled it. Also, shifts were observed in leaf composition, including water content as well as carbon and nitrogen elemental ratios, among other traits. Considering the nature of the observed MPs' impacts on plants and soils, Machado et al. proposed a causal model (Fig. 1) in which the effects of MPs on plant performance would start with plastics altering the soil biophysical environments of bulk soil and rhizosphere [28]. These physical, chemical, and biological effects of plastics in soils would then be perceived by plants, resulting in changes of biomass allocation, tissue chemical composition, and symbioses.

A recent study by Bosker et al. [37] found that germination of seeds was significantly reduced with 8-h exposure to MPs (Fluoro-Max Green Fluorescent Polymer Microspheres), with increasing concentration and the largest particle size

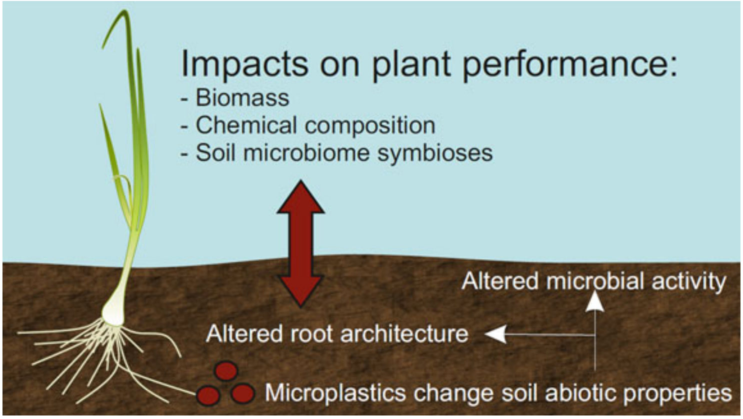


**Fig. 1** Mechanisms proposed by Machado et al. [28] affecting plant performance

(4.8 μm) leading to more significant effects. However, by 24 h the effects of treatment were indistinguishable, with all treatments reaching close to 100% [37]. Root growth was also influenced by MPs which were variable depending on the particle type (50 nm particles led to a significant increase in growth, while 500 nm particles led to a significant decrease in growth) and were again only observed up to 24-h exposure after which time effects were not seen [37]. The results of this study are interesting, as studies comparing particle sizes generally show that the smaller the particle, the greater the negative effect on plants [38, 39]. Effects such as delayed germination and root growth could have implications for the timing and development of crops, although these effects were only seen over acute timescales.

Boots et al. [16] confirmed many of these previous findings when assessing the response of soil biophysical properties when the ryegrass (*Lolium perenne*) and the rosy-tipped earthworm (*Aporrectodea rosea*) were exposed to three types of microplastics (polylactic acid, high-density polyethylene, and clothing fibers). They also observed a reduction in the shoot high on polylactic acid treatment and a reduction on animal biomass by polyethylene [16]. Soil pH and water-stable aggregates were also affected. Therefore, these authors concluded that there is evidence that the tested microplastics can affect the basic, but crucial, soil properties, potentially triggering further impacts on soil ecosystem functioning [16].

Indeed, the mechanisms of intrinsic (direct) toxicity of MPs in plants remain less explored [40]. It is hypothesized that, as particle size decreases, small MPs present higher biological reactivity and, therefore, more potential for chemical-like toxic effects [7]. That is due to the fact that particles within the range of few micrometers are not expected to be taken up into the root. The opposite is true for NPs, however. The rhizodermis of roots would constitute the primary barrier for nanoplastic uptake, and although the mechanisms for nanoparticle uptake in plants are not fully described [41], it is accepted that particles within the range of few nanometers could enter into plant roots, potentially causing alteration of cell membrane and intracellular molecules and generation of oxidative stress [42]. Such information is still to be experimentally demonstrated for NPs, but if so, it might constitute a relevant point of entrance of plastics into the constitution of continental ecosystems [40].

It is currently clear that there is a diverse array of mechanisms by which MPs can influence plant performance, i.e., from affecting biophysical environment perceived by symbionts (e.g., plant pollinators or AMF) [7, 28] up to direct intrinsic toxicity [37]. Thus, some authors have argued that effects at plant community levels cannot be discarded [40]. That is because the very properties of plant communities are often related to soil structure and composition [9]. The changes in evapotranspiration caused by microplastic films, fibers, and fragments may affect local water cycling, contributing to more pronounced drought and selection of drought-resistant plant species, not to mention the changes in soil microbiomes discussed above. Rillig et al. [40] argued that effects on plant communities are likely to occur in areas with more severe microplastic contamination, which would place natural reserves near agricultural fields or cities under higher concern. Given that plants provide the basis of nutrition for most of continental life on earth, it is essential that we work to understand possible implications of MP pollution on plant growth and diversity.

## *2.3 Animals and Microplastics in Soil*

There are a fast-growing number of studies on effects of MPs in animals. Many studies have looked at the interaction of micro- or nanoplastics on earthworms [11, 43–48] and on isopods [49, 50] representing the macrofauna. However, fewer studies address the mesofauna, although this organism group forms a huge part of the soil's diverse community. Collembola, oribatid mites, and nematodes form the most abundant groups among the soil mesofauna. From this group, especially Collembola [12, 13, 51], mites [13], nematodes [49, 50, 52], and also enchytraeids [13] were among the studied organisms.

Soils under agricultural and other human uses can be significantly contaminated [53, 54] by various plastic types of different sizes and shapes, containing a broad range of additives that can be found in various concentrations. This might have significant effects on soil animal communities [43, 44]. For instance, earthworms and Collembola can transport particles and beads horizontally and vertically which increases in predator-prey situations [9, 12, 13, 51].

The interaction with the particles or fibers will differ depending on the body size [43–45, 52, 55] and the developmental stage of the respective organism. This means that the same particle might have negative effects on, e.g., the adult stage of an organism but not (or a different effect) on larval/nymphal stages of the same organism. Together with the highly complex food web dynamics in soil, it is very difficult to disentangle the various effects of diverse particle size and chemistries. Additionally, there are open questions on whether soil organisms ingest MPs, if they show avoidance behavior, if they can distinguish between "food" and "nonfood" (as shown for nematodes in Kiyama et al. [56]), or if the shear presence of synthetic particles might already affect their fitness [51]. Although the knowledge about interactions in soil macro- and mesofauna with nano- and microplastic increases, many aspects still remain in the dark. Especially studies in the field have not been conducted so far. This might partly be due to nonexisting standardized methods for the quantification of the MPs but also due to a lack of soil ecotoxicological expertise and framework of relevance for detecting impacts from microplastic exposure [57].

Earthworms are well-known representatives of the soil's macrofauna, their biology is well understood, and many studies exist in regard to the effect of micro- and NPs on these organisms and vice versa. In 2017, Rillig et al. showed that *Lumbricus terrestris* can transport microplastic spheres ranging from 710 to 2,800 μm along the soil profile potentially via burrowing activity, egestion/casts, or adherence to the earthworm exterior [11]. Lwanga et al. [43] showed higher numbers of burrows as well as denser burrow walls in the presence of MPs. This vertical transport decreases the degradation of the particles, i.e., within the soils, there are suboptimal light and temperature conditions necessary to reduce the sizes of polymers before any biodegradation can occur [58]. Potential anaerobic conditions in deeper soil layers may also decrease or even inhibit oxidative degradation.

Apart from the transport by earthworms, there have been many studies on various aspects concerning the fitness of mostly two earthworm species, *Lumbricus terrestris* and *Eisenia fetida*, respectively. Lwanga et al. [44] observed increased mortality and reduction in growth of *L. terrestris* at certain microplastic concentrations in the bulk soil and an increase of microplastic particles smaller than 50 μm in size in the casts which suggests size-selective egestion as well as reduced biomass in a different study [55]. For *Eisenia fetida*, growth inhibition was reported at concentrations $>1\%$ (w/w in dry soil) [59]. A similar result was seen by Boots et al., who found high-density polyethylene particles 0.48–316 μm in size to cause a significant reduction in biomass of the earthworm *Aporrectodea rosea* [16]. However, Prendergast-Miller et al. [60] did not find lethal effects of microfibers nor active avoidance behavior. Lahive et al. exposed the small earthworm *Enchytraeus crypticus* to two different polymer types (nylon and polyvinyl chloride) and two different sizes of nylon [61]. They found smaller nylon particles (13–18 μm) to have a more significant effect on reproduction (compared to 90–150 μm), with a dose-response relationship effect: increasing concentrations led to a greater negative effect [61]. Nylon also had a significantly greater effect than polyvinyl chloride at comparable particle sizes and concentrations [61].

Another currently open question is whether plastic particles can act as vectors for pesticides or other substances. It is suspected that persistent organic and inorganic pollutants could adsorb easily to plastics and thus affect the soil community. Hodson et al. [48] found that high-density polyethylene MPs could indeed act as a vector for toxic zinc to earthworms. In contrast, Rodriguez-Seijo et al. [62] did not find similar evidence MPs sprayed with chlorpyrifos. Additionally, *Eisenia* individuals even showed avoidance behavior at the highest contamination level in this study. In contrast, *Lumbricus terrestris* did not show avoidance behavior in respect to microfibers in a study by Prendergast-Miller et al. [60]. Wang et al. [63] also concluded from their results that MPs do not enhance the uptake of substances as they observed only very low bioaccumulation. In the same study, the authors report that although polyethylene and polystyrene were definitely ingested by *Eisenia fetida*, this did not induce oxidative stress. In 2018, Rodriguez-Seijo et al. found contrasting results: *Eisenia* individuals did indeed show an oxidative stress [64]. *Lumbricus terrestris* responded likewise to exposure to polyester fibers in a study by Prendergast-Miller et al. [60]. Despite the fact that such changes in the oxidant defense systems did not significantly affect the molecular level, they still observed lower cast production. In a study from Rodriguez-Seijo et al. [46], histopathological changes and a triggered immune response were observed in *Eisenia andrei* when exposed to MPs.

Several effects might arise from the ingestion of MPs by soil organisms. For instance, it has been shown for the earthworm *Eisenia andrei* that microplastic particles can damage the gut system and induce stress effects in the immune system [46]. To which extent this might also be true for collembolans needs to be studied in the future. In addition, it is not clear if microarthropods are able to selectively egest MPs as it has been suggested for the earthworm *Lumbricus terrestris* [44]. Collembolans regenerate the midgut epithelium together with the cuticle at each molting cycle. Thus, one can speculate that collembolan's biology might prevent them from severe damage to tissues or inflammation of gut tissues as reported for nematodes [52]. However, Zhu et al. [13] recently showed that MPs have impacts on the composition of the gut microbiome of *Folsomia candida*, resulting in a change of the isotopic signature (higher $\delta^{15}N$ and $\delta^{13}C$ values). These biochemical changes were linked to the inhibition of growth and reproduction (the latter by 28.8%) and potentially also general feeding behavior. That is because higher $\delta^{15}N$ and $\delta^{13}C$ values might indicate a change in the metabolic turnover and also growth rate. Under similar conditions, Yu et al. [65] reported a decreased reproduction, avoidance behavior, and an altered gut bacterial diversity at varying concentrations of polyethylene particles in artificial soils.

In addition to earthworms, PET microfibers in soils have been shown to negatively affect terrestrial snails (*Achatina fulica*), increasing oxidative stress and leading to gut inflammation after chronic exposure [66]. Additionally, this study found that the integrity of the fibers could be compromised following ingestion and egestion, with visible cracks and deterioration of the fibers. This implies that ingestion could cause them to become weak and thus more susceptible to further degradation. Similar observations have been made following ingestion of MPs by Antarctic krill, whereby ingestion led to fragmentation of MPs and the formation of NPs within the gut, suggesting that ingestion of particles could enhance breakdown of MPs to smaller MPs and NPs [67]. This is likely the result of the digestive processes – for example, it has been shown that freshwater snails especially will actively store inorganic mineral particles within their guts to aid with the grinding of food [68], while krill have mandibles specifically for grinding [69]. Lwanga et al. [45] found gut bacteria in the earthworm *L. terrestris* which were able to decay parts of ingested low-density polyethylene particles, resulting in smaller particles. Such processes are therefore designed to facilitate the breakdown of larger particles and could feasibly lead to the degradation of plastic particles in other organisms that rely on similar mechanisms. The study by Lwanga et al. [45] is potentially significant because, if this is to be confirmed, it might imply that symbiotic gut bacteria of other organisms might also be evolving enzymatic machinery to degrade plastics. This would certainly represent an interesting topic for further detailed investigation.

The nematode *Caenorhabditis elegans* has been the subject of a number of microplastic studies, with exposure to MPs often leading to negative effects. For example, Lei et al. [70] exposed *C. elegans* to a range of differently sized micro- and nanoplastic particles (100 nm, 500 nm, 1, 2, and 5 μm, each at a concentration of 1 mg $L^{-1}$ over 72 h). They observed significant effects on a number of endpoints including decreased growth, abnormal behaviors, increased markers of oxidative stress, and mortality. Depending on the endpoint measured, the size of the particle often made a difference to the observed response [70]. Kiyama et al. [56] demonstrated the ability of *C. elegans* to actively accumulate carboxylate microspheres of 0.5 and 1 μm in diameter. Whether consumption of such particles has negative effects on growth and health of terrestrial nematodes is not yet known.

Selonen et al. [50] conducted a very interesting experiment, analyzing the effects of polyester fibers of different lengths on enchytraeids, isopods, springtails, and oribatid mites offered in food or in soil at five concentrations (0.02–1.5% (w/w)). They only found slight effects, however, e.g., the reproduction of enchytraeids was decreased to 30% with increasing fiber concentration. This effect was only found in treatments with long fibers which were only seldomly ingested, which suggests that the observed effect might be due to changes in the environmental conditions or physical harm outside of the enchytraeid. However, short fibers were clearly ingested by enchytraeids and isopods and increased with increasing concentration in the soil treatment. Although the authors conclude that short-term exposure might not have severe effects to soil invertebrates, potential long-term effects might indeed be relevant for their fitness and would need to be tested in the future [50]. In addition, this study shows that ingestion of fibers actually happens with unknown long-term consequences.

A study with different polymers and concentrations found that polyamide, polyethylene, polypropylene, and polyvinyl chloride can have effects on growth, reproduction, and survival at concentrations as low as 0.5 mg $m^{-2}$ on agar. Polymer type did not significantly influence the effects observed. A parallel study showed polystyrene particles to have significant size-dependent effects, with the greatest observed effects seen with the intermediate-sized particle (1 μm compared to 0.1 μm or 5 μm) [52, 70]. Further, NPs (100 nm) have been seen to cause transgenerational effects on nematodes, with a significantly reduced brood size in adults exposed to 10 μg $L^{-1}$ and in the resulting F1 generation, produced from adults exposed to 100 μg $L^{-1}$ [71]. Zhu et al. [13] found that enchytraeids which ingested NPs had a reduced gut bacterial diversity and body weight. An interesting article by Kiyama et al. [56] reports that nematodes might be able to discriminate between "food" and "nonfood" based on size, taste, and olfaction. This ability has been described so far for earthworms [46], and extrapolations to other soil organisms need to be studied in the future.

In most studies, only one species is looked at. However, especially in soils, the food web is very complex. How MPs affect the species fitness might have a strong influence on the food web's stability. For example, once a collembolan is eaten by a Mesostigmatid mite, the transfer of these particles to the next higher trophic level might be in progress. Likewise, micro- and nanoplastics in the fecal pellets, eggs, and decaying collembolan biomass could be ingested again by earthworms, constituting another unexplored pathway of plastics back into terrestrial food webs. In this sense, what happens to the next higher trophic level is not known and should be further studied as the biomagnification of plastic polymers, additives, and adsorbed substances along the food chain may severely harm the fitness of the respective organism groups. Huerta Lwanga et al. [55] found evidence for the transfer of MPs from earthworms to chickens which underlines the necessity of studying food chains not only above- or belowground separately but combined to understand the fate and also the accumulation of micro- and nanoplastic particles, which may eventually reach the human table.

In summary, there are several indications and controversies about the potential effects of MPs on soil organisms. These partly contrasting results underline the necessity of further studies taking into account several other soil organisms or even whole communities under different contamination levels, with different particle types and sizes, and in varying soil types. All these factors can presumably have very different effects on the fitness of the organisms but also on the soil health in general. For example, earthworms exposed to high microplastic contamination might suffer from increased mortality, and this might feedback to soil porosity; this has now become supported by the findings of Lwanga et al. [43, 44, 55] and Ng et al. [58].

## 3 Factors Accounting for the Observed Effects of Microplastics on Soil and Terrestrial Organisms

According to the currently accepted conceptual model of MPs' effects on terrestrial systems, several factors account for toxic and environmental changes derived from microplastic pollution [7]. Size, hydrophobicity, charge, density, and shape are among the properties expected to significantly affect the soil system. In fact, some evidence has been proposed for size [26] and hydrophobicity. Shape is especially important according to the work from Machado et al. [26, 28], in which fibers consistently affected more the soil biophysical environment compared to beads and fragments. Probably because fibers entangle soil particles and shape aggregates, they are expected to interact differently with soil biota.

Therefore, MPs represent an entire class of contaminants, each with their characteristic (and not necessary similar) kind of effects. The various combinations of polymer matrix, chemical makeup, additives, persistence, surface, sizes, and shapes implies that MPs might elicit a variety of environmental impacts. As previously mentioned, polyester microfibers (at concentrations up to 0.40%) can affect soil biophysical properties more strongly than polyamide beads or polyethylene fragments (at concentrations up to 2.00%). Evidence for a particle-dependent diversity of effects has been obtained for beads, fragments, and fibers, as well as biodegradable microplastic [36], films [72], and NPs [73]. Rillig et al. [40] highlighted that foams and various other materials are still to be investigated.

### *3.1 Microplastic Particle Size and Shape*

In the experiments from Machado et al. [26, 28], polyester microplastic fibers were often the type of largest physical impacts, e.g., the strongest effects on soil structure and interactions with water. Their linear shape, size, and flexibility make those particles substantially different from most natural components of soils. This, in turn, potentiates the effects on such soil biophysical properties and plant responses. For instance, rootability is inversely proportional to soil bulk density [74]. As fibers cause a remarkable effect on soil bulk density, green onions exposed to PES presented ~40% increase in root biomass associated with a decrease of ~5% in root diameter [28]. In such context, the longer and finer roots contributed to changes in leaf elemental composition (N/C) and other proxies for plant physiological status or nutrient availability.

Compared to polyester fibers, Machado et al. [28] observed less pronounced effects attributable to high-density polyethylene fragments, which can be attributed to the fact that the fragments were more similar in size and shape to the natural particles present in the tested sandy loam soil [40]. Notwithstanding, high-density polyethylene and other test fragments triggered substantial decreases in soil bulk density, changes in water dynamics, alterations of soil microbes, and consequently the response of spring onions. Therefore, future comparative studies should look at various soil types, climatic regimes, temporal scales, and microplastic properties to test whether anthropogenic particles of different types and shapes are an important driver of terrestrial global change.

When particle sizes get smaller, potential microplastic hazards might become more concerning. For fish, it has been shown that nanoplastic was able to cross the blood-brain barrier causing behavioral disorders including slower feeding rates and higher risk of being predated [75]. Although the brain of soil microarthropods is anatomically distinct from fish, neurons, receptors, functional enzymes, and molecules were very well preserved throughout evolution [7]. Thus, we still need to think about potential harmful effects on behavioral patterns in insects, especially in terms of predation risk. Micro- or nanoparticles have not been experimentally observed inside the tissue of soil microarthropods. Likewise, it needs to be tested to which extent this might affect the organisms in general besides the effects on the nervous systems or equivalents. However, a recent study shows the decrease in movement of the collembolan *Lobella sokamensis* in the soil pore system at a concentration of polystyrene and polyethylene bead and fragment of various sizes and at concentrations of 1,000 mg/kg soil [51]. When considering the effects such as observed by Kim and An, it is important to mention that it is unclear whether the effects of MPs are of direct toxicity or an indirect response to environmental change. The abovementioned effects of MPs on the soil structure [26] might have negative effects on the feeding behavior of soil organisms. On the other hand, soil organisms also exhibit effects on the soil environment by, e.g., constructing biopores [51] in which microplastic particles can get trapped very quickly.

The potential effects of the attachment of nanoparticles to the cuticle of microarthropods should not be underestimated. The cuticle of Collembola is composed of several layers which is able to protect the individual from fouling by antibacterial and antifungal compounds but at the same time allowing gas exchange and exhibiting hydrophobic characteristics. Depending on their size and charge, plastic particles could get attached to the setae but also to the cuticle due to their hydrophobic surfaces [54] and might also pass it via the pores. The pore channel diameters range from 200 nm to 2 μm, potentially allowing a range of plastic particles to cross the cuticle.

Another, more extreme example is the oribatid mite family Damaeidae, which attaches soil particles to their cuticle and hence might act as vector of transport not only for microbes [12] but also for micro- and nanoplastic particles with unknown consequences for the individual or receiving environment. The colonization of particles by microorganisms can increase soil aggregation, meaning that the particles could potentially become bound even tighter into the soil matrix which potentially increases the resistance of plastics to degradation to more than 100 years [25, 76]. Further studies are definitely needed to clarify potential interaction between various particle sizes, the soil environment, and the inhabiting soil organisms and their behavior.

### 3.2 *Microplastic Particle Chemistry*

As plastics degrade, increasing in particle number and decreasing in size, soil microfauna such as bacteria and fungi may consume them [77, 78]. However, with their high C/N ratio, this new food source would leave those feeding on it lacking nitrogen and other nutrients causing them to seek it out elsewhere in the soil and leading to immobilization – the conversion of inorganic compounds to organic compounds, rendering them inaccessible to plant roots. Such immobilization could have negative impacts on plant production. Furthermore, the high C content of plastics could throw off soil organic C quantification, a method used to assess land fertility, which could negatively impact crop production [77].

Some studies revealed unexpected ways via which plastic particles directly triggered effects in soil and plant traits. Certain primary MPs (polyamide beads of 15 μm) seem to contain considerable amounts of compounds from the manufacture that are adsorbed to the particles or were loosely interacting with the polymer matrix [28]. Nitrogen (component of the amide group in polyamides) could be easily released into soils, which supported a nearly twofold increase in leaf N content and total biomass alongside a relative decrease in the root-to-leaf ratio [28]. Thus, remaining monomers leached into the soils causing a chemical change comparable to fertilization. These primary polymer-based pellets may contain additives (e.g., lubricants) on the surface and often organic phosphite antioxidant additives in the bulk that are easily transformed to organic and inorganic phosphates. It is reasonable to hypothesize that the situation would be different in the case of aged polymer particles in real-world soils [28].

Beyond the main polymer matrix of plastic, many thousands of plastics are further processed by the addition of chemical additives before being shaped [7]. Four main groups of additives, functional additives, colorants, fillers, and reinforcements, represent a dizzying array of organic and synthetic chemical compounds which are added to the polymer backbone of plastics to imbue them with desirable characteristics such as tensile strength, reflectivity, clarity, hardness, etc. These compounds can leach from the chemical matrix of plastics as they degrade and enter the surrounding environment [7, 19, 25]. The long-term effects of leachates entering agricultural soils are unknown.

Fuller and Gautam [17] showed that in Australian top soils near roads and industrial areas, the concentration of MPs may reach up to 7% by weight. At this level, severe effects of leaching chemicals were observed. For example, nonvolatile organochlorines from polyvinyl chloride caused geochemical changes in the soil, altering soil chlorinity [17]. Another risk is the leaching of substances like bisphenol A and phthalates, which might exhibit estrogenic and other endocrine activities in vertebrates and some invertebrates [79]. Moreover, when larger plastic particles become smaller, the surface-volume ratio increases. Consequentially, the many additives bound in a physical and not chemical way to the polymer matrix might face increased probability of leaching of plasticizers and other compounds [80]. In fact, it is conceivable that the low-level toxicity associated with plastic microparticles, due to its pervasive nature, results in a selective pressure of species and species traits and unknown consequences for functional bio- but also phenotypic and genetic diversity [7], potentially creating new niches, e.g., oviposition sites, in the soil environment.

### *3.3 The Properties of the Soil System*

Just as the various properties of MPs might account for different effects, the impacts could vary immensely with soil characteristics, i.e., natural particle origin, mineralogy, granulometry, texture, etc. [9]. At the time of writing this chapter, most of works were performed in sandy loam soil with rather simplified representations. Diverse effects should be expected if soils richer in silt and clay particles would be used [26]. Same could be said if other soil structures would be considered. For instance, pores larger than 0.08 mm (macropores) can enhance movement of soil particles, because sedimentation and sieving are not as pronounced, and they enhance the movement of water [9]. It implies that macropores may indirectly influence how fast microplastic particles are moved in the soil.

Other soil processes similarly affecting MPs' potential fate and effects are the events of soil cracking and wet-dry cycles [9, 26, 28, 81]. Common in agricultural soils with expanding mineral types is the appearance of cracks and fissures when the soil dries. These cracks could work as potential highways for plastic particles to arrive at deeper soil layers [9]. This process could then enter positive feedback as soils with MPs are reported to present increased evapotranspiration and more intense formation of superficial cracks.

The soil biota also would play a key role in intensifying or minimizing impacts of MPs [36]. Earthworms, microarthropods, and even decomposing roots create large biopores that might contribute to the movement of MPs inside the soil in a similar fashion as macropores [9]. It has been proposed that fungal hyphae may also serve as preferential paths for movement of particles in the cm range, as has been demonstrated for the transport of bacterial cells. The cell membrane and walls of filamentous fungi has been shown to adsorb large quantities of nano- and small MPs [82]. Thus, it is conceivable that fungi might contribute to transport of NPs within soils.

Finally, certain human usage of soils might potentiate MPs' effects [81]. The plowing and harvesting of agricultural activities can be very effective for moving MPs into the deeper soil layers [9]. For instance, moldboard plowing brings about an inversion of the top soil layer. The consequence is that MPs on the surfaces will be transferred to the layer at the plowing depth whenever this moldboard is employed [9]. Likewise, the revolving of soils for the harvest of plant portions below the soil surface (e.g., potatoes, carrots) can also serve to incorporate microplastic into the various soil horizons.

## 4 Final Considerations and Future Directions

MPs can affect physicochemical and biological parameters of the soil. Those effects potentially have direct serious environmental consequences, such as changes in agricultural productivity and dysfunction of soil biogeochemical cycles [26, 83, 84]. In order to access the risk (i.e., the probability) of such hazards, there are some questions that need to be addressed.

Perhaps a crucial open question is what are the realistic contamination levels of MPs in soils around the globe? This will require an environmental simultaneous identification of particle size, shape, and polymer type. None of the currently available microplastic quantification performed in environmental soils analyzes these three parameters concomitantly [7, 85]. Moreover, the level of NPs in soils is unknown.

Another lack of relevant information relates to the poor design of experiments with MPs regarding their ability to provide relevant ecotoxicological information. Far too many of the studies on MPs consider a single or maximum of two exposure levels. This renders information not useful to extract the valuable dose-response relationships of organisms to realistic MP exposures. These Dose-response relationships associate exposure to environmental effects and are fundamental to determine levels of MPs in soils that would impact important soil functions. By now, we do not know yet how these curves look like in terms of shapes and slopes [26]. In fact, it is not even clear how dose-response relationships for microplastic effects depend on the soil characteristics. Thus, it is not possible to scientifically devise at the risk current MPs might pose. The research from Machado et al. [26, 28] seem to suggest that some of these curves might not be monotonic. This needs to be confirmed by further investigations; it would imply that new ecotoxicological frameworks would need to be developed.

There is also growing concern about soil micro- and macrofauna unwittingly ingesting these particles and then transferring it upward to the higher trophic levels of terrestrial food webs [55]. Not only earthworms but another ubiquitous soil inhabitant, the nematode, has also been experimentally shown to ingest MPs [56]. These two organisms' low rank on the food chain represents a potentially significant source of microplastic contamination in the terrestrial food web. Preliminary experimental results as well suggest a high likelihood that both saprobic soil fungi and the roots of common crop plants can take up nanoplastic particles of various surface charges [82, 86]. It would be important, for example, to know if such occurrences in natural and agricultural settings could lead to both bioaccumulation and biomagnification of plastic particles and which effects this could lead to. A better understanding of the impacts of MPs on terrestrial systems thus requires special focus on soils. It is within soils that MPs could affect the natural functioning of terrestrial ecosystems in important ways other than eliciting direct lethal toxicity [7, 26, 28]. For instance, the impacts on water cycling (water holding capacity of soils and evapotranspiration rates) are relevant for numerous processes from micro-scale microbial activity to watershed-scale water management [87].

A direct area of interest between the above-discussed microplastic effects and sustainability is on food security [7]. Agriculture is an important contributor to microplastic pollution. The agricultural industry has benefited substantially from the advent of plastic greenhouses, mulches, irrigation systems, and microplastic capsules for fertilizers and pesticides [81, 88]. Some of these plastics are left out in the field, are tilled into the soil with the next rotation, and steadily increase the pool of environmental MPs. Further contamination of agricultural soils with MPs was stemmed from the application of sewage sludge as fertilizer. Nizzetto et al. [14] estimated that up to 430,000 and 300,000 tons of MPs were added per year in the form of sewage sludge to farmlands in Europe and North America, respectively. The proportion of MPs in the topsoil accumulate with further sludge amendments, and in agricultural settings where soil is amended by sewage sludge in China, for example, Zhang and Liu [18] determined that per kilogram of topsoil between 7,000 and 43,000 particles (mostly fibers) of MPs can be found.

Some effects on lab mimicking a simple agroecosystem suggests potential yield losses [16]. It remains unclear what types of impacts the increasing fraction of plastics in the soil which grows our crops on could have on global food production. The same could be stated for soil biodiversity [7, 28, 59]. The physical structure of soil and the dynamic nature of its components are crucial factors when choosing the appropriate soil for a given crop. Aspects such as the soil bulk density, water retention, texture, porosity, aggregation, and others affect the suitability for crop production. Soils need to be cohesive but not too dense or compacted as to hinder microbial and root growth throughout them or to impede water and air circulation [74]. Another important characteristic of soils, aggregate stability, or the ability of aggregates to overcome external forces and remain integrated, is a good indicator of soil organic matter as well as being important for the creation of pore spaces of various sizes which allow for their effective circulation of air and water [6]. Zhang and Liu [18] found that 72% of all MPs found in their test fields (92% fibers) were involved in soil aggregates, while only 28% were not involved. The exact properties which determine microplastic involvement in aggregate formation are yet unknown and require further observation. Also, the drying and desiccation of soils caused by MPs could lead to negative impacts on plant growth. Issues related to water retention will likely be exacerbated in the context of climate change which should increase the unpredictability of weather patterns and rainfall and cause increases in droughts [40]. Looking more closely, smaller MPs known as NPs ($<0.1$ μm) could potentially accumulate on soil surfaces, altering surface characteristics of various soil matrix components and influencing the normal interactions surrounding soil aggregation due to their hydrophobic properties. Little research has been conducted on potential effects of nanoplastic particles on soil structure, and further research is required to disentangle microplastic roles in soil systems.

In summary, MPs can affect soil physicochemical and biological parameters, and a current assessment of the potential risks of those particles cannot be accurately achieved because there are numerous unsolved questions. The simultaneous quantification of size, shape, and chemistry of plastic microparticles will be essential to provide insights on the realistic levels and potential environmental effects. Alongside, the provision of precise dose-response relationship is fundamental. Despite the lack of data, it is clear that MPs could affect the soil biophysical environment, triggering responses in microbes, plants, animals, and biogeochemical cycles in various terrestrial ecosystems across the globe. The extent and intensity of such change is largely unknown. Given the incipient evidence, however, it seems likely that non-negligible effects of microplastics on soil biodiversity and their environmental services might be already in place.

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