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Microplastic effects on plants

Summary

Microplastic effects in terrestrial ecosystems have recently moved into focus, after for about a decade research was limited to aquatic systems. While effects on soil physical properties and soil biota are starting to become apparent, there is not much information on consequence for plant performance. We here propose and discuss mechanistic pathways through which microplastics could impact plant growth, either positively or negatively. These effects will vary as a function of plant species, and plastic type, and thus are likely to translate to changes in plant community composition and perhaps primary production. Our mechanistic framework serves to guide ongoing and future research on this important topic.

Keywords: microplastic, nanoplastic, pollution, roots, soil structure, plant-microbial interactions, plant community, global change

I. Microplastic in terrestrial ecosystems

Oceans and aquatic ecosystems have been the focus of microplastic contamination research for the last decade, and the notion that terrestrial ecosystems may also be afflicted was developed comparatively recently (Rillig, 2012). Microplastics in the aquatic phase are simply more obvious (and visible), compared to soil. For soil, the first analytical methods have only recently been developed (He *et al.*, 2018), and method development is an ongoing and challenging process for this medium, compared to aquatic systems. And, finally, given that effects in aquatic systems were mostly related to the existence of an additional particle (which could be confused with food items) and surface (which could adsorb and enrich contaminants), this aspect seemed of minor importance in soil, which is a particle-rich environment with an already massive internal surface area (Machado *et al.*, 2018a).

Microplastics have now been found in soils of many terrestrial ecosystems (Zhang & Liu, 2018), including agricultural fields (Piehl *et al.*, 2018), cities and industrialized areas (Fuller & Gautam, 2016), and also rather remote areas (Scheurer & Bigalke, 2018). Once deposited at the soil surface *via* a variety of input routes (Bläsing & Amelung, 2018), several pathways, including biological activity, contribute to the incorporation of microplastic particles into the

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soil (Huerta-Lwanga *et al.*, 2017; Rillig *et al.*, 2017a; Rillig *et al.*, 2017b; Ng *et al.*, 2018). The decomposition rate of microplastics in soil is currently unknown, and the assumption is that this material is persistent, and will thus accumulate (Rillig, 2012).

Given that this material will not go away soon, research on microplastic effects in terrestrial ecosystems is now well underway. The initial results have shown that microplastic may adversely affect soil biota, such as earthworms (Huerta-Lwanga *et al.*, 2017), and that microplastic can change soil biophysical properties, including soil aggregation, bulk density and water holding capacity (Machado *et al.*, 2018b; Wan *et al.*, 2019). An initial focus on earthworms, other soil biota and soil physical effects is a very reasonable starting point, but what about effects on plants? We have very little information on this (Qi *et al.*, 2018), and this paper is intended to serve as a guide for ongoing and future research on this topic.

II. Different types of microplastic

It is important to acknowledge that microplastic pollution is far from a monolithic issue: plastic comes in a dazzling range of chemical makeup, additives, persistence, surface properties, sizes and shapes. These materials will have different properties in the environment, and also different effects in terrestrial ecosystems. For example, Machado et al. (2018b) have already shown that microfibers (added at concentrations from 0.05% to 0.40%) appear to affect soil physical properties more strongly than beads (which were added at concentrations from 0.25% to 2.00%).

The initial focus of microplastic research has been on polyethylene beads, because they are easily obtained from suppliers in standardized form. Experimental work has moved to include microfibers (Machado *et al.*, 2018b), and more recently also biodegradable materials (Qi *et al.*, 2018), films (Wan *et al.*, 2019) and nano-sized materials (Awet *et al.*, 2018). Other types are not yet explored, for example foams, and various compound materials.

We think that at least particle size and shape will have also very different effects on plant growth and might also present different concerns for food safety (Table 1, Fig. 1). Similar hypotheses could, with more information available, also be proposed for different chemistries and other aspects of microplastics (particularly surface characteristics).

Table 1. Hypothesized effects of different types of microplastic particles on plants, and potential food safety concerns for crops. Listed are the major effects, with secondary effects highly likely (see Fig. 1).

Microplastic type	Major hypothesized effect pathway	Expected effect size and direction (+, -) for plant growth	Potential concern for food safety (in an agricultural context)
Beads, fragments	Effects similar to minor changes in soil texture	Minor	Minimal
Fibers	Soil structure, bulk density changes	Large (+)	Unclear
Films	Increased soil water evaporation	Intermediate (-)	Unclear
Biodegradable	Nutrient immobilization in soil (short-term)	Intermediate (-)	Decreased nutrient contents
Nanoplastic	Toxicity to plant roots and soil microbiota	Minimal to intermediate (-)	Plastic ingestion (uptake), especially for consumed belowground plant portions

III. Hypothesized effects on plants

What kind of mechanisms could be important to consider to understand microplastic effects on plant performance (Fig. 1)? We think that there are several potential mechanisms at play, in part as a function of microplastic type (Table 1); these will all act concurrently, but will be discussed separately below.

Altered soil structure

Microplastics can be viewed conceptually as a soil physical contaminant (Machado *et al.*, 2018a), and initial data suggest that, indeed, microfibers have led to lowered soil bulk density (Machado *et al.*, 2018b). This could translate directly to reduced penetration resistance for plant roots, and better soil aeration, and thus increased root growth (Zimmermann & Kardos, 1961). However, other effects are also possible: plastic films (2, 5, and 10 mm size fragments, added at 0.5% and 1.0%) have been shown to create channels for water movement, leading to increased water evaporation (Wan *et al.*, 2019). This could lead to soil drying, with potentially negative consequences for plant performance.

Alterations to soil structure can have many other, secondary effects. It will be inevitable that a shift in a major soil parameter such as soil structure will cause changes in soil microbial community composition, even though it is difficult to predict such shifts, and also their functional consequences. If such changes also affect root symbionts, including mycorrhiza and N-fixers, this could translate to plant growth consequences.

Changes in the overall structure of soil can also affect the process of soil aggregation (Machado *et al.*, 2018b), with microfibers having had a negative effect on soil aggregation in this particular field study. Positive effects on soil aggregation are also possible if microfibers serve to entangle soil particles and thus aid in the soil aggregate formation process component. Soil aggregation, by influencing in turn soil structure, will have consequences for soil aeration and root growth, as discussed above.

We currently do not know if nanoplastic can affect soil structure as well, for example by exerting toxic effects on soil microbes important for the production of binding agents, or via altering the polarity of soil aggregate surfaces.

Nutrient immobilization

Plastic particles have a very high content of carbon (Rillig, 2018), and most of this carbon will be relatively inert, since the material does not readily decompose. Eventually this material will slowly be degraded, and given the very wide C:N ratio, this will lead to microbial immobilization. Given the very slow decomposition of most plastic materials, this will occur on a timescale that is likely irrelevant for any biological effects. However, effects like this are expected to be much more pronounced for microplastic material with lower persistence, for example biodegradable plastics. A first experimental study has shown that plant performance parameters (e.g. leaf area) decreased in the presence of biodegradable plastic residues added at 1.0% in a mixture of sizes (Qi *et al.*, 2018), possibly due to microbial immobilization (even though this was not measured in the study), which supports this idea. Such effects are likely comparatively short-lived but will be important to keep in mind when interpreting experiments on plant growth effects.

Contaminant transport or adsorption

Microplastics can add a surface to soil with different properties, for example hydrophobic surfaces. Contaminants with certain properties (e.g. hydrophobicity) could enrich on such particles and they could potentially be stable for longer periods of time. Phytotoxic substances already present in microplastics before they arrive in the soil (e.g., when added during manufacture), could be transported into soil with these microplastic particles. Toxic substances, either adsorbed onto surfaces (and within the particle ‘ecocorona’; Galloway *et al.*, 2017) of microplastic particles in the soil, or already contained in the particles could negatively affect plant roots or their symbionts, potentially translating to negative plant growth effects. Alternatively, the adsorption of contaminants to microplastic surfaces could make other pollutants less available to soil biota and plants, thus exerting a protective effect. The latter has been observed in aquatic environments (Kleinteich *et al.*, 2018; Rehse *et al.*, 2018), and such effects may be transferable also to soils. Thus, there currently is considerable uncertainty whether pollutant effects will be enhanced or decreased by microplastic.

Direct toxicity

As particle size decreases, effects on biota are hypothesized to become more chemical/ toxic, as opposed to physical (Yang *et al.*, 2017; Machado *et al.*, 2018a). While microsized particles are not expected to be taken up into the root, the situation is different for nanoplastic particles. The existence of nanoplastic particles in soil has never been demonstrated, since current extraction and quantification methods either miss them, or do not deliver any size information. However, it seems quite likely that nanoplastics are present in the environment, if microplastic particles fragment into smaller pieces (Fig. 1; nanoplastic is < 100nm). For example, Lambert and Wagner (2016) have demonstrated the appearance of nanoplastics from the degradation of polystyrene plastic cup lids under lab conditions (no soil). The rhizodermis of roots would likely be the primary place of interaction and barrier for nanoplastic uptake. Although the mechanisms underlying nanoparticle uptake in plants are poorly described (Yang *et al.*, 2017), it is accepted that nano-sized particles could enter into plant roots, and potentially cause damage (e.g. alteration of cell membrane, intracellular molecules, and generation of oxidative stress) (Navarro *et al.*, 2008) – but there are no data for nanoplastic at present. If the plant is a crop, this could also mean that plastics may enter into the part of the plant that is intended for human or livestock consumption, thus entering the food chain (Bouwmeester *et al.*, 2015). Nano-sized plastic particles could also be strongly sorbed onto soil surfaces, and thus rendered less effective. However, Awet et al. (2018) documented short-term detrimental impacts of polystyrene nanoplastics on soil microbial and enzymatic activity (in the absence of plants). Either way, effects on plant performance are expected to be at best neutral.

Soil microbial community and root symbionts

Plant performance depends heavily on soil biota and their diversity (Wagg *et al.*, 2014), and in particular on root colonizing microbes, including N-fixers, pathogens and mycorrhizal fungi (Powell & Rillig, 2018). If microplastic causes changes in soil structure, these could influence microbial communities in soil (Vallespir Lowery & Ursell, 2019), potentially affecting mineralization rates, and communities of root-colonizing symbionts (Fig. 1). Likewise, nanoplastics might also affect the soil-borne phase of symbionts, such as arbuscular mycorrhizal fungi, through toxic effects. This has not been shown for nanoplastic, but other nanoparticles can have effects on mycorrhizal functioning (Feng *et al.*, 2013). We currently do not know the effects of microplastics or nanoplastics on the community composition of soil or root colonizing microbes, and thus the consequences of any such changes are at this point completely unclear; however, this needs to be a research priority.

IV. Plant community-level effects

As discussed above, there is a wide range of plastic types, and also a diverse set of different mechanisms for affecting plant performance, with also different effect signs (Fig. 1, Table 1). It is thus quite clear that different plant species in a community could be affected to a different degree by the addition of microplastics (either as mixtures or single types). Thus, microplastics have the potential to affect plant diversity and community composition, and there are several mechanisms that can underpin shifts. For example, plant community properties are related to soil structure (e.g. soil aggregation) (Pohl *et al.*, 2012; Peres *et al.*, 2013). Thus, the significant effects of various microplastics types on soil structure have the potential to affect plant community composition. Plastic films, which increased soil water evaporation (Wan *et al.,* 2019), may lead to more pronounced drought and subsequently promote the growth of drought-resistant plant species in a community. Moreover, the soil microbial community strongly influences plant community composition, productivity and diversity (Wagg *et al.*, 2014; van der Heijden *et al.*, 2016; Powell & Rillig, 2018). Changes in soil microbial composition or root-colonizing symbionts following microplastic addition may thus further influence plant community composition. For instance, if microplastic additions reduce soil microbial diversity or the abundance of root-colonizing symbionts, plant diversity could be decreased, due to the often positive effects of soil microbial diversity or root-colonizing symbionts on plant diversity (Wagg *et al.*, 2014; van der Heijden *et al.*, 2016). Such effects on plant communities are more likely to occur in areas with higher microplastic pressure, and thus are perhaps a greater concern near agricultural fields or cities.

V. Conclusions

Microplastics are contaminants of concern; given their ubiquity they need to be regarded as a factor of global change (Machado *et al.*, 2018a). At present we know next to nothing about the effects of this factor of global change on plants. We outline several mechanisms through which these materials could affect plant performance. Some of these mechanisms will result in positive effects on roots and plant growth, others will have negative consequences. These effects will vary as a function of plant species, and thus are likely to translate to changes in plant community composition and perhaps primary production. It will be a challenge to understand what the effect size and direction of such effects at the individual plant to ecosystem level will be, as a function of ecosystem type and degree and type of contamination. It is critically important to test for these effects, as plants are important players in the climate system: widespread effects, even with relatively small effect sizes as one might expect for plant performance, could have important repercussions for ecosystem functions and climate feedbacks.

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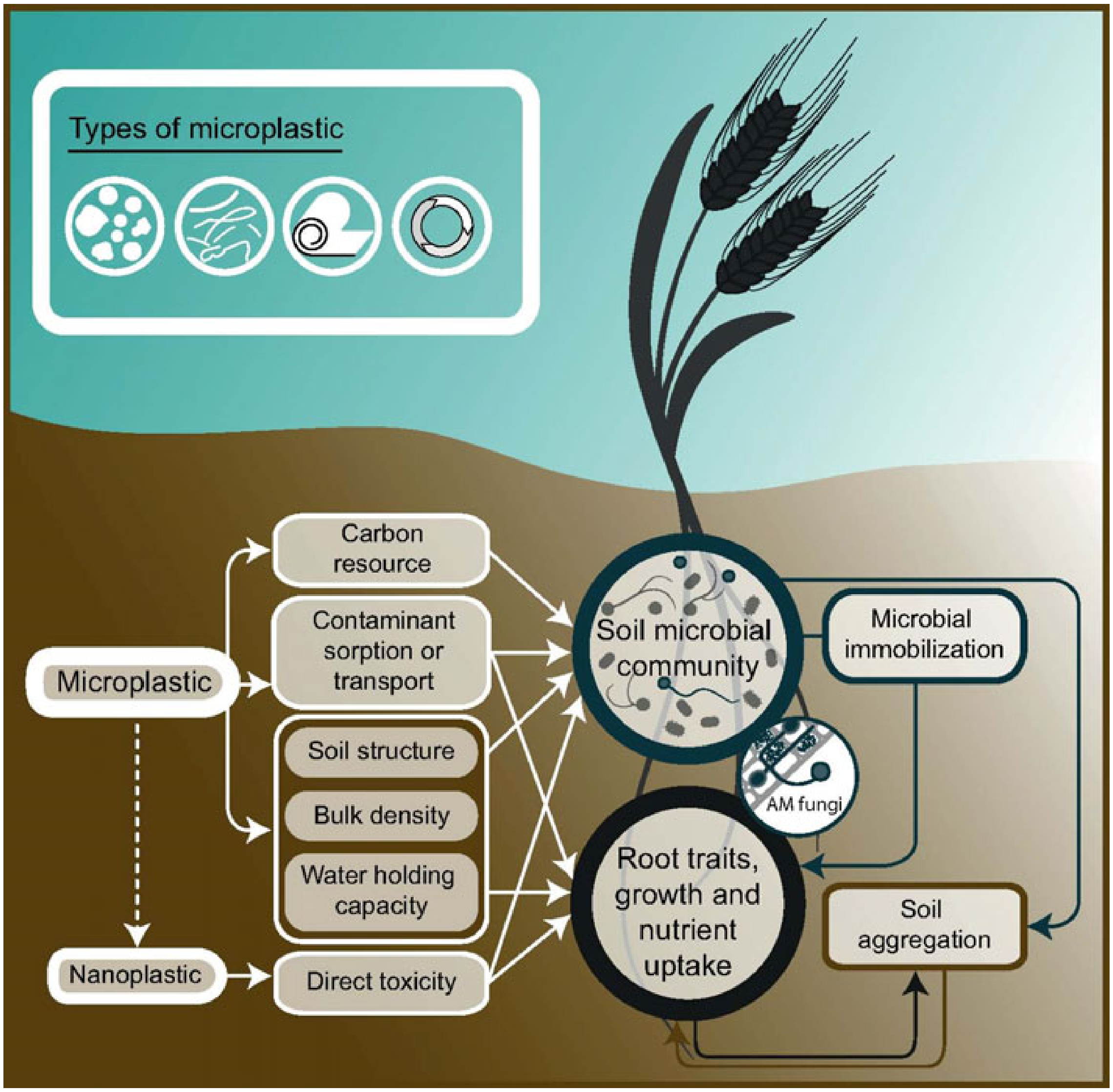
Figure legends

Fig. 1 Concept diagram showing the various mechanisms via which microplastic particles could affect plant growth (see the '*Hypothesized effects on plants*' section for details). The relative importance of these pathways is expected to differ as a function of microplastic types (insert: fragments/ beads, fibers, film, and biodegradable; see Table 1 for major hypothesized effects by microplastic type). AM, arbuscular mycorrhiza.


Types of microplastic
Carbon resource
Contaminant sorption or transport
Microplastic
Soil structure
Bulk density
Water holding capacity
Nanoplastic
Direct toxicity
Soil microbial community
Microbial immobilization
AM fungi
Root traits, growth and nutrient uptake
Soil aggregation