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Review

Sources, migration, accumulation and influence of microplastics in terrestrial plant communities

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ABSTRACT

Microplastics pollution have become an environmental issue of global concern due to the extensive use and unreasonable disposal of plastics. The effects of microplastics on terrestrial ecosystems, especially on plant ecosystems, have attracted growing attention. However, the recent researches mainly focus on the individual plants, and study on the plant community-level is still very rare. This review introduces sources of microplastics in plant communities, elaborated the migration and accumulation of microplastics in plant communities, and highlights the effects of microplastics on plant communities, especially on community biomass and community structure. Future research works should further identify the effects of microplastics on different plant communities, especially in areas with higher microplastic pressure such as agricultural fields or around cities, in order to assess the ecological risks of microplastics in the environment more comprehensively.

1. Introduction

Microplastics (plastics less than 5 mm in size, including nanoplastics which are smaller than 0.1 μm) are being recognized as a new important global change factor, potentially influencing terrestrial ecosystems (Huang et al., 2020; Khalid et al., 2020; Machado et al., 2018). Microplastics are generally divided into two categories: primary microplastics which are manufactured to perform certain functions, such as cosmetic microplastics and resin particles used as industrial raw materials, and secondary microplastics formed by fragmenting and reducing the volume of large plastic waste through physical, chemical, and biological processes (De Falco et al., 2019; Duis and Coors, 2016; Kole et al., 2017). Microplastics can directly or indirectly enter aquatic ecosystems and terrestrial ecosystems (Guo et al., 2020; Khalid et al., 2020; Zhou et al., 2020). However, unlike the microplastics in the marine environment, those in terrestrial systems have received less scientific attention (Horton et al., 2017; Renzi et al., 2018). Due to the lower ability of migration in soil, the concentration of microplastics in terrestrial environments will probably increase over time (Xu et al., 2020). Recent studies have shown that microplastics can accumulate in higher plants and have negative effects on plant growth (Li et al., 2020; Qi et al., 2018). Since plants are a basic living component of terrestrial ecosystems (Sutherland et al., 2010), understanding the interactions between microplastics and plant communities is crucial (Lozano and Rillig, 2020). Microplastics have now been found in soils of many terrestrial ecosystems all over the world, including agricultural fields, cities and industrialized areas, and also rather remote areas (Table 1). As the main source of microplastics in plant communities, soil is currently facing serious microplastic pollution, which indicates that plant communities are suffering from varying degrees of microplastic pollution. Therefore, the effects of microplastics on plant communities is indeed a matter of concern.

Microplastic accumulation in plants can have direct ecological effects and implications for agricultural sustainability and food safety (Sun et al., 2020). They can be adsorbed onto the root surface, or be absorbed by roots, fruits, and vegetables and, consequently, accumulate in these structures (Hernandez-Arenas et al., 2021; Jiang et al., 2019b; Meng et al., 2021). The effects of microplastics on plants vary depending on their types, shapes, sizes, and concentrations. As such, several kinds of microplastics have distinct effects on plant growth, as observed in *Lactuca sativa*, *Triticum aestivum*, *Allium fistulosum*, and *Phaseolus vulgaris* under different conditions (de Souza Machado et al., 2019; Jiang et al., 2019b; Meng et al., 2021; Qi et al., 2018) (Table 2).

The effects of microplastics on plant performance have been observed in individuals and populations of some species, but not within

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a community (Zang et al., 2020). For example, *Triticum aestivum* (common wheat) and *Lolium perenne* (grass) showed reduced biomass after exposure to films and fibers, respectively, whereas *Allium fistulosum* (crop) exposed to fibers showed the opposite effect (Boots et al., 2019; Qi et al., 2018). Similarly, the morphological traits (e.g., root length) of *Plantago lanceolata* (forb) and *A. fistulosum* displayed contrasting responses to microplastics (de Souza Machado et al., 2019; Kleunen et al., 2019). These different individual responses suggest that the addition of microplastics to the soil has varying effects on different plant species within a community, which may affect plant productivity and community structure (Rillig, 2012).

Most of the current papers only focus on the study of individual agricultural plants, and much attention has been devoted to assessing the potential toxicity of microplastics to plants on an individual level, there is still a scarcity of information on the potential toxicity to the plant communities. However, plants exist in the form of community in nature, and compared with community studies, the study of an individual plant has little significance in the actual production and life. Because plant communities are composed of several species and have complex hierarchical structures, the research on plant communities requires more complex experiments and longer experimental cycles. In addition, studies assessing the effects of microplastics on plant communities can better reflect the actual impact of microplastic pollution on the ecological environment. For these reasons, plant communities were the subject of this review, wherein the effects of microplastics on plant communities, particularly on their biomass and structures, will be elucidated.

2. Sources of microplastics in plant communities

In terrestrial environments, soil is the main medium for microplastics to enter plant communities. Further, by analyzing results of current research on soil microplastic pollution, we can infer the main sources of microplastics in plant communities. In addition to soil, microplastics found in plant communities mainly originate from the introduction of surface runoff and agricultural irrigation water, the residual decomposition of agricultural mulching film and plastic waste, land use of municipal sludge, and the deposition of microplastics from the atmosphere. Among them, the air-borne MPs may directly affect plant aboveground parts and also enter the soil to affect roots.

1) Plastic mulching is an important form of introduction of microplastics into soil systems, which can affect agricultural plant communities (Huang et al., 2020; Ng et al., 2018). Plastic residues have become a serious environmental problem in regions with intensive use of plastic mulching. For instance, data show that the area covered by plastic film in China, the world's largest consumer of plastic mulches, has been increasing by an average of 660,000 ha every year since 1994, reaching more than 18 million hectares in 2015 (Huang et al., 2019). The presence of plastic film residues can change soil properties such as increasing porosity and changing aggregate structure, which may further affect the soil enzyme activity, as well as the microbial functional diversity of the soil (Hodson et al., 2017; Liu et al., 2017). For instance, Huang et al. (2019) observed that the activities of urease and catalase in soil were significantly increased after 15 days of treatment with microplastic amendment (2000 fragments per kg soil). Ultimately, these effects will have a significant impact on the biomass and structure of plant communities. For example, plastic film can increase soil water evaporation, which may lead to more obvious drought, thus promoting the growth of drought-resistant plants in the community (Wan et al., 2019).
2) The main sources of irrigation water are surface water, groundwater, and purified sewage, which contain a variety of microplastics, including different shapes (fibers, fragments, and particles) and materials (polyethylene terephthalate, polyethylene, polypropylene, and polyvinyl alcohol) (Gatidou et al., 2019; Jiang et al., 2019a; Panno et al., 2019). The quantity of microplastic pollution ranged from 4.83×10^2 to 1.25×10^5 particles/m^3 depending on the source of irrigation water (Gatidou et al., 2019; Jiang et al., 2019a; Zhao et al., 2015, 2014).
3) The general treatment steps of sludge extraction used in sewage treatment plants (e.g., sedimentation, drying, sterilization, composting, etc.) are not capable of eliminating microplastics. Since sludge compost is applied to the farmland soil as fertilizer, it becomes the main source of microplastics in the soil (Bayo et al., 2021; Li et al., 2018; Zhao et al., 2015). The total amount of microplastics discharged into farmland soil through sludge in Europe is between 1.25×10^2 and 8.50×10^2 t/year (Nizzetto et al., 2016), while the magnitude of other places' pollution remains unclear.
4) Additionally, very small particles or fibers can be spread further by becoming air-borne (originating from landfills or other surface deposits) and then entering terrestrial systems through atmospheric deposition (Dris et al., 2016; Rillig, 2012). The latest research shows that the deposition flux of microplastics in the atmosphere can reach 1.46×10^5 particles/(m^2·a), of which more than 95 % are fibers, and more than 50 % are microplastic particles smaller than 0.50 mm, with the main components including polyesters, polyvinyl chloride, polyethylene, and polystyrene (Chen et al., 2020). Plant communities in urban agglomeration areas are significantly affected by atmospheric microplastic deposition (Klein and Fischer, 2019). In fact, Dris et al. (2016) found that the amount of fibrous microplastic pollution entering Paris' urban area through atmospheric deposition reached 3–10 t/year.

3. Migration and accumulation of microplastics in plant communities

The mechanisms that allow the absorption and accumulation of

Table 1
Soil microplastics pollution in some parts of the world.

Countries and regions	Type of microplastics	Type of soil areas	Size of the microplastics	Abundance	Reference
Shanghai, China	PE, PP, PVC	Farmland soils in suburbs	< 5 mm	78.0 ± 12.9 particles kg^{-1}	(Liu et al., 2018)
Guangdong, China	PS, PP, PVC	E-waste dismantling zone	< 1 mm	9450 ± 9520 numbers kg^{-1}	(Chai et al., 2020)
Switzerland	PE, PS, PVC	Floodplain soil	< 2 mm	55.5 mg kg^{-1}	(Scheurer and Bigalke, 2018)
Mexico	PE, PS	Traditional Mayan home gardens	5 − 150 mm	0.87 ± 1.9 particles·g^{-1}	(Huerta Lwanga et al., 2017)
Murcia, Spain	PE	Agricultural soil covered with plastic mulch	< 5 mm	2116 ± 1024 particles kg^{-1}	(Beriot et al., 2021)
Sydney, Australia	PVC, PE, PS	Industrial area soils	< 1 mm	300 − 67,500 mg kg^{-1}	(Fuller and Gautam, 2016)
Metropolitana, Chile	PE, PP	Agricultural soils from sewage sludge disposal	< 1 mm	18,000 − 41,000 particles kg^{-1}	(Corradini et al., 2019)
Korea	PE, PPP, ET	Rice cultivation fields	1.0–1.58 mm	160 ± 93	(Kim et al., 2021)
Germany	PE, PS	Agricultural soil	< 1 mm	0.34 ± 0.36	(Piehl et al., 2018)

microplastics in individual plants have been studied extensively. In lettuce, wheat, and other plant species such as *Arabidopsis thaliana*, fluorescent tags were added to microplastics (Jiang et al., 2019b; Li et al., 2019; Sun et al., 2020), and it was found that on a micron scale, these materials were trapped and adsorbed onto the root surface due to the mucus secreted by the root cap, and could not permeate the root cortex or reach the stele through apoplastic barriers and the free space between root cells (Li et al., 2019). However, submicron or nanometer microplastic particles can enter the plant body through the root system and reach the aboveground part of the plant using the transpiration pull of the vascular system of the roots and stems, along with water and nutrients (Li et al., 2020). In addition, Li et al. (2020) found that some microplastics could penetrate the stele of plants using the crack-entry mode at sites of lateral root emergence, permeate the xylem conduit in the roots, and be transported to the stem and leaf tissues (Fig. 1). Based on the above experimental results, it can be concluded that only some submicron and nanometer microplastics can enter the plant through the free space between root cells, and they need a certain transpiration pulling force to reach the aboveground part of the plant. Most microplastics are still aggregated and adsorbed on the surface of plant roots. Therefore, the plant root is the main accumulation place of microplastics.

No study has hitherto focused on the regulation of microplastic distribution at the community level. However, by combining the evidence obtained for individual plants with the characteristics of plant communities, it may be inferred that the distribution of microplastics within plant communities will be affected by the properties of the microplastic particles themselves, the effects of plant absorption on microplastics, soil organisms, and other factors.

1) The shapes, sizes, and chemical properties of microplastic particles directly affect their migration within plant communities. Microplastic particles of approximately 5~50 nm, which is the size of plant cell wall pores, are more easily adsorbed to the seed epidermis or root cell wall (Bosker et al., 2019). In addition, because of Stokes sedimentation and the aggregation and deposition of microplastics, medium-sized microplastic particles are easier to transport, while those with small or large sizes are easier to retain (Besseling et al.,

Table 2
Effects of microplastics on different plants.

Specie	Microplastics				effect	Reference
	Type	Shape	Size	Concentration		
Lactuaca sativa	PS	spherical	D: 0.23 ± 0.04 μm D: 0.98 ± 0.09 μm	10 (mg/mL)	The polystyrene is transported through the vascular assembly to the stem and leaves	(Li et al., 2020)
	LDPE	film	L: 4~10 mm	1% (w/w)	The total biomass decreased and the composition of rhizosphere bacterial community changed	(Qi et al., 2018)
	Bio	film	L: 50 μm~1 mm	1% (w/w)	The mixing of volatile organic compounds in the rhizosphere was affected, and the composition of bacterial community in the rhizosphere was changed	
Triticum aestivum	LDPE	film	L: 6.92 ± 1.47 mm W: 6.10 ± 1.37 mm	1% (w/w)	The biomass decreased, the fruit biomass and leaf number decreased	(Qi et al., 2018)
	Bio	film	L: 6.98 ± 1.61 mm W: 6.01 ± 1.31 mm	1% (w/w)	The growth of plant height was inhibited, the fruit biomass decreased, the aboveground biomass decreased, and the root/shoot ratio increased	
	LDPE	spherical	D: 11.3 μm	100, 500, 1000 (mg/L)	The germination rate was inhibited, but the root length, bud length and wheat biomass had no significant changes	(Ze-quan et al., 2010)
	PS	spherical	D: 100 nm	5% (w/v)	The root length increased, the root/shoot ratio decreased, and the biomass increased while the germination rate did not change	(Lian et al., 2020)
	PA	microsphere	D :15~20 μm	2% (w/w)	the total biomass increased, and the total root length and mean diameter increased	
Allium fistulosum	PES	fiber	L: 5 mm D: 8 μm	0.2 % (w/w)	The total biomass and root biomass increased, the total root length and mean diameter increased, and the root microbial activity increased	(de Souza Machado et al., 2019)
	PS	particle	547~555 μm	2% (w/w)	Root biomass increased significantly, total root length and mean diameter increased	
Phaseolus vulgaris	LDPE	particle	53~1 000 μm	0.5 %~2.5 % (w/w)	Aboveground and root biomass had no significant change	(Meng et al., 2021)
	PLA	particle	53~1 000 μm	0.5 %~2.5 % (w/w)	1.5 %, 2.0 % and 2.5 % treatments significantly reduced root and aboveground biomass	
Calamagrostis epigejos	PES	fiber	L: 1.28 ± 0.03 mm D: 30 μm	0.4 % (w/w)	The root biomass increased, but the total biomass had no significant change	(Lozano and Rillig, 2020)
Allium cepa	PS	particle	50 nm	0.1 (g/L) 1.0 (g/L)	The germination rate did not change and the root length was inhibited	(Giorgetti et al., 2020)
Lolium perenne	HDPE	particle	102.6 μm	0.1 % (w/w)	The root biomass increased and the root/shoot ratio increased	(Boots et al., 2019)
	PLA	particle	65.6 μm	0.1 % (w/w)	The germination rate decreased and the bud length was inhibited	
Daucus carota	PES, PA, PP	fiber	L: 5 mm	0.1 %, 0.2 %, 0.3 %, 0.4 % (w/w)	Aboveground biomass increased with the increase of concentration, and root mass increased when the concentration was 0.4 %	(Lozano et al., 2021)
	LDPE, PET, PP	film	L: 5 mm W: 5 mm	0.1 %, 0.2 %, 0.3 %, 0.4 % (w/w)	Aboveground biomass and root mass decreased with increasing concentration	
Zea mays	HDPE	particle	100~154 μm	0.1 %, 1%, 10 % (w/w)	There was no significant change in plant biomass, even a slight increase.	(Wang et al., 2020a)
	PS	particle	100~154 μm	0.1 %, 1%, 10 % (w/w)	The plant biomass decreased, especially the root system.	
	PLA	particle	100~154 μm	0.1 %, 1%, 10 % (w/w)	High concentration (10 %) significantly reduced plant biomass, while low concentration (0.1 %, 1%) had no significant effect.	

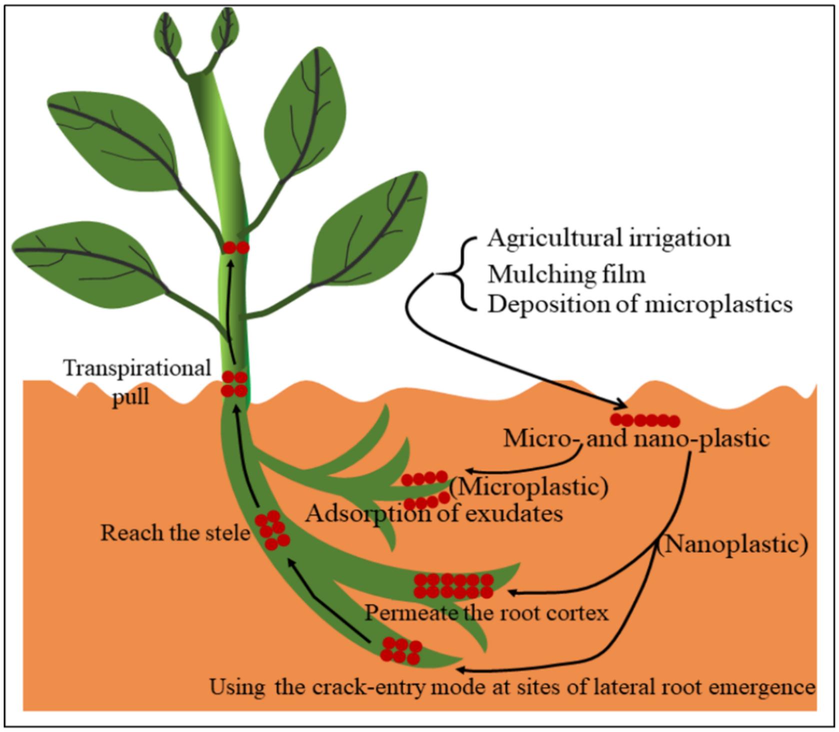

Fig. 1. Pathways of micro- and nano-plastic entrance in plants.

2017). Sun et al. (2020) found that the absorption effect of microplastics with different surface charges was different in *Arabidopsis thaliana*, and the experiment proved that the aggregation promoted by the growth medium and root exudates can limit the uptake of nanoplastics with positive surface charges.

2) The varying absorption effects of different plant species on microplastics are the main reason for their uneven distribution in plant communities. For instance, microplastics may be more likely to be absorbed by plants with strong or well-developed roots (Ramanayaka et al., 2020). In addition, the root movement, expansion, and water absorption have a great influence on the migration of microplastics. Moreover, the macropores left by decomposing roots may be conducive to the entry of microplastics present in the soil into the plant (Rillig et al., 2017).

3) Rillig et al. (2017) studied the effects of earthworms on the migration of microplastic particles of different sizes and revealed that, due to earthworm activity, small particles (710~850 μm) were found in underlying soil layers (10 cm), large particles were extremely concentrated in intermediate layers, and there were no microplastic particles in the surface soil layer, suggesting that earthworms can affect microplastic migration within soil layers and the particle size selectivity of this phenomenon (Wang et al., 2021). Similarly, Maass et al. (2017) investigated the migration of microplastics driven by collembolans and obtained the same results. These studies indicate that soil organisms influence the migration of microplastics in the soil, which will in turn affect the distribution of microplastics in plant communities.

4. Effects of microplastics on plant communities

4.1. Effects of microplastics on plant community biomass

Microplastics can affect the biomass of plant communities through a variety of mechanisms, such as direct toxicity, changes in soil structure, nutrient immobilization and effects on soil microbial community and root symbionts (Khalid et al., 2020; Rillig et al., 2019). Meanwhile, the influence of microplastics on the biomass of plant is related to many factors, such as the shape of plastic particles, plastic degradability, and type and growth stage of the plant (Besseling et al., 2014). Therefore, the changes of biomass of different species of plants exposed to microplastics may be different in the same plant community. (Fig. 2)

Qi et al. (2018)'s study that focused on the effects of wheat exposure to plastic mulch found that different types of microplastic residues affected the biomass of both the aboveground and underground parts of wheat plants during vegetative and reproductive growth, with biodegradable plastic mulch showing stronger negative effects than polyethylene. Similarly, when *Lolium perenne* was exposed to different types of microplastics, researchers found that the germination of *L. perenne* seeds was inhibited, and biodegradable polylactic acid (PLA) inhibited the growth of new seedlings more significantly than conventional high-density polyethylene (HDPE) (Boots et al., 2019). One plausible explanation for decreased germination is that microplastic particles block the pores of seed capsules, as observed by confocal microscopy evaluation (Bosker et al., 2019). Although the exact mechanism causing the stronger inhibitory effect of PLA plastics remains unclear, some researchers speculate that in *L. perenne*, it may be attributed to potential stress caused by the degradation of PLA byproducts (Boots et al., 2019). During degradation, PLA is broken down into lactic acid oligomers by the enzymes of certain microorganisms (Qi et al., 2018). Moreover, PLA may combine with nutrients present in the soil, thus inhibiting the growth of plants because of increased difficulty in obtaining nutrients. The sizes and shapes of the residues produced by PLA plastics may also be important factors influencing plant growth. Moreover, researchers also found that root biomass was greater when HDPE was present. Since plants expand their root system to cope with stressful environments, the increased root biomass of *L. perenne* exposed to HDPE may be indicative of stress caused by the presence of microplastics. Additionally, it is likely that the root biomass increase observed in soils with microplastics can be linked to reduce soil bulk density and increased soil macroporosity, which ultimately improves aeration and facilitates the penetration of roots in the soil matrix (Lozano and Rillig, 2020).

Microplastics have the characteristics of small particles and strong hydrophobicity, and have strong adsorption capacity for organic pollutants. Taking the typical antibiotic pollutant ciprofloxacin as an

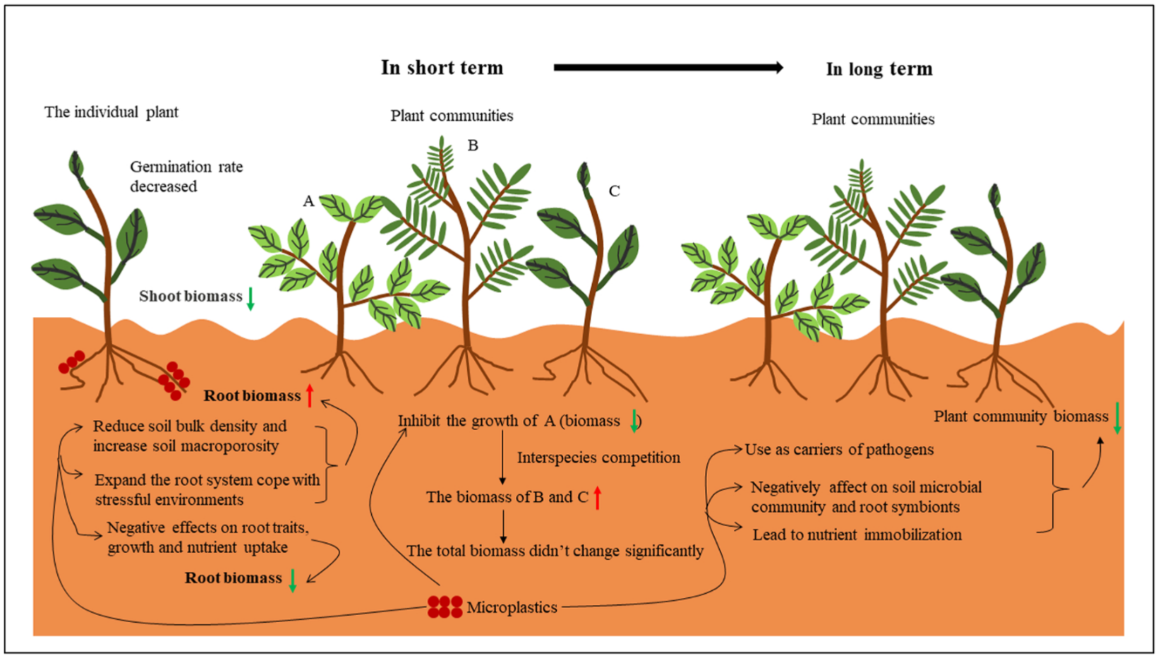

Fig. 2. Effects of microplastics on plant community biomass.

example, the researchers found that polypropylene microplastics have a strong adsorption capacity for ciprofloxacin (CIP) and can significantly affect the transport behavior of CIP in porous media (Wang et al., 2020c). In addition, the combined effect of microplastics and heavy metals is also an important factor affecting plant biomass. Wang et al. (2020a) found that the combined effect of microplastics and Cd will promote the transformation of plant performance and root symbiosis, which brings additional risks to agroecosystem and soil biodiversity.

Moreover, the decline of plant biomass caused by the negative effects of microplastics on soil biota composition cannot be ignored. To date, the ingestion of microplastics in the soil has been demonstrated in the anecic earthworm, and polystyrene microplastics has been shown to effectively inhibit the growth of earthworms, as well as to have a significant lethal effect on earthworms at high exposure concentrations ($\geq$0.5 %), which were possibly explained by the damage in the self-defense system of earthworm(Cao et al., 2017; Huerta Lwanga et al., 2016; Prendergast-Miller et al., 2019). Huang et al. (2019) demonstrated that microplastics can act as carriers of pathogens and have negative effects on soil microbial communities thus further strongly influences plant community productivity.

The effects of microplastics on individual plant biomass also affect plant communities. Understanding the mechanisms causing the effects of microplastics on the biomass of different plant species allows more effective prediction of the effects of microplastics on plant communities. Because of the complexity of species, plant interaction within a community is another important factor that affects the biomass of a plant community. Lozano and Rillig (2020) reported that in a simulated temperate grassland ecosystem, microplastics added to the soil increased the shoot mass of *Calamagrostis* and *Hieracium* by approximately 66 % and 85 %, respectively, but microfibers decreased the shoot mass of *Holcus* and *Festuca* by approximately 78 % and 51 %, respectively. This may be attributed to the allelopathy of community plants as well as the selection of dominant plant species by microplastics within the community. Under the influence of microplastics, *Festuca* showed decreased growth, whereas *Hieracium*, a genus that can reduce the germination and growth of neighboring species through allelopathy, demonstrated increased growth. Allelopathy mainly affects the growth, development and metabolism of other plants through various compounds secreted by plants, and reduces their biomass. The main mechanisms are as follows. 1) Inhibiting seed germination and seedling growth, such as phenolic compounds and hydrolyzed tannins can hinder the physiological effect of gibberellin; ferulic acid and 3,4-dihydroxybenzoic acid can inhibit the activity of indole acetic acid oxidase (Bains et al., 2009). 2) Inhibiting protein synthesis and cell division. For example, coumarin and ferulic acid can prevent phenylalanine from integrating into protein molecules. Cinnamic acid can also inhibit protein synthesis, thus affecting cell division. 3) Inhibiting photosynthesis and respiration. For example, scopolamine can cause stomatal closure and decrease photosynthetic rate. Phenolic acid can reduce the chlorophyll content and photosynthetic rate of soybean (Bais et al., 2003). However, some studies have found that, although microplastics may decrease the biomass of some plants, microplastic tolerance in some plants may increase their biomass due to competition for water, nutrients, space, and other resources within the community, thus offsetting the negative community effects of microplastics. Therefore, although the biomass of different plants in the community showed obvious differences when exposed to microplastics, the correlation between the total biomass of the community and microplastic pollution was not significant under this condition.

Hitherto, most studies analyzing the effects of microplastics on plant biomass have stayed at the population level, with few experimental results to supporting the effects of microplastics on complex plant communities (Nor and Obbard, 2014). However, it is certain that the influence of microplastics on the biomass of plant communities is affected by many factors. In simple plant communities, microplastics may inhibit plant germination, and community biomass will consequently decline in the short term (Rillig et al., 2019). However, as there are fewer individuals competing for resources such as space, water, and nutrients, other plants in the community may display a more efficient use of these resources, resulting in higher levels of biomass for plants. For some complex plant communities, Lozano and Rillig (2020) found that in the short term, microfibers could improve plant productivity and change the morphological characteristics of roots. However, as microplastics can be used as carriers of pathogens, under the long-term influence of microplastics, soil pathogens may accumulate and plant growth may be inhibited (Huang et al., 2019). Additionally, toxic substances already present or absorbed onto microplastics would negatively affect not only plant roots (their growth, and thus rhizodeposition) but also soil biota composition and microbial activity, which could further influence plant growth and reduce the biomass of plant communities (Qi et al., 2020).

4.2. Effects of microplastics on plant community structure

The effects of microplastics on plant community structure are mainly reflected in the species diversity and spatial structure. (Fig. 3)

Microplastics can affect community structure by promoting allelopathy among different species. As aforementioned, Lozano and Rillig (2020) found that microplastics can increase the growth of *Hieracium*, while growth of its neighbor *Festuca* is inhibited by allelopathic effects. This suggests that the reduction in soil bulk density due to the effect of microplastics promotes the growth of *Hieracium* but has a detrimental allelopathic influence on *Festuca*. Thus, microplastics may promote the aggregation of plants of the same species, thereby affecting the horizontal structure of a plant community. Moreover, microplastics can also affect the soil physicochemical properties, such as soil pH, soil organic matter, water-stable aggregates and so on, resulting in a more unfavorable soil environment for plant growth, thus affecting the horizontal structure of plant communities (Boots et al., 2019; Fu et al., 2018). Boots et al. (2019) found that there were significant differences in the distribution of water-stable soil aggregates among different microplastic treatments. Compared with the soil without microplastics, the number of microaggregates (<63 μm) in the soil exposed to HDPE and PLA (0.1 % w/w) decreased significantly. Good soil structure and high water-stable soil aggregates are very important to improve soil fertility and promote water movement. Therefore, this negative effect of microplastics will have a potential impact on soil organic matter content and soil moisture. Similarly, the high carbon content of microplastics could lead to microbial N immobilization, with consequences for plant community productivity and composition (Iqbal et al., 2020). Fu et al. (2018) found that soil water was the most important factor controlling the change of grassland vegetation community structure in semi-arid area, followed by soil organic matter, total nitrogen and total phosphorus. For the wetland grassland community, the soil water content is the main factor affecting the distribution pattern of the wetland grassland community in Poyang Lake, and the soil nutrient content is the secondary factor (Gang et al., 2010). For sandy dryland soil, soil nutrient gradient is the main soil limiting factor of sandy grassland community distribution pattern (Zuo et al., 2007).Therefore, we have reason to believe that the changes in soil physicochemical properties caused by microplastics will have a potential impact on the community structure of some plant communities, especially those with low species richness or poor original environment.

Moreover, changes in soil microbial composition or root-colonizing symbionts following microplastic addition may thus further influence plant community composition (van der Heijden et al., 2016; Wagg et al., 2014). The results of Qi et al. (2020) show that microplastics can exert selective pressure on distinct microbial taxa as anthropogenic substrates. For instance, there is a relatively high abundance of bacteria taxa affiliated with the genus *Saccharibacteria* when exposed to low-density polyethylene plastics (Qi et al., 2020). In addition, biodegradable microplastics can induce high amount of dodecanal in rhizosphere soil, which will have a negative effect on the growth of plant root fungi (Wang et al., 2020b). Therefore, the addition of microplastics may reduce the soil microbial diversity or the abundance of root colonization symbionts and other factors conducive to plant community diversity, thus affecting the species diversity of plant communities.

Microplastics can also affect plant community structure by promoting the growth of highly invasive plant species, such as *Calamagrostis*, especially in environments with abundant water (Rebele, 2014). *Calamagrostis*, a genus of species that is widespread throughout temperate Eurasia, has invaded several high-value semi-natural steppes in central Europe due to its clonal growth nature, and has caused a decline in the biodiversity of steppe plant communities (Házi et al., 2011). *Holcus* is a genus of species native to Europe that shares the rapid clonal growth characteristics of *Calamagrostis* (Házi et al., 2011; Tesitel et al., 2017). Their co-existence could potentially reduce the invasiveness of *Calamagrostis* species by creating a more competitive environment (Collins, 2009). However, studies found that microplastics tended to inhibit the growth of *Holcus*, which indirectly boosted the growth of *Calamagrostis* (Lozano and Rillig, 2020). Although no research has proved that microplastics can directly promote the growth of some invasive species and affect community biodiversity, this way of indirectly promoting species invasion by inhibiting native competitive species is also worthy of attention. Invasive alien plants will trigger a noteworthy effect on indigenous ecosystems, especially on biological diversity and community stability.

The influence of microplastics on plant community structure may not be reflected in only these two aspects, as current research is still limited to communities of herbaceous plants; as such, influence on woody plants and even more complex plant communities is still unknown. For example, for some complex woody plant communities, the vertical

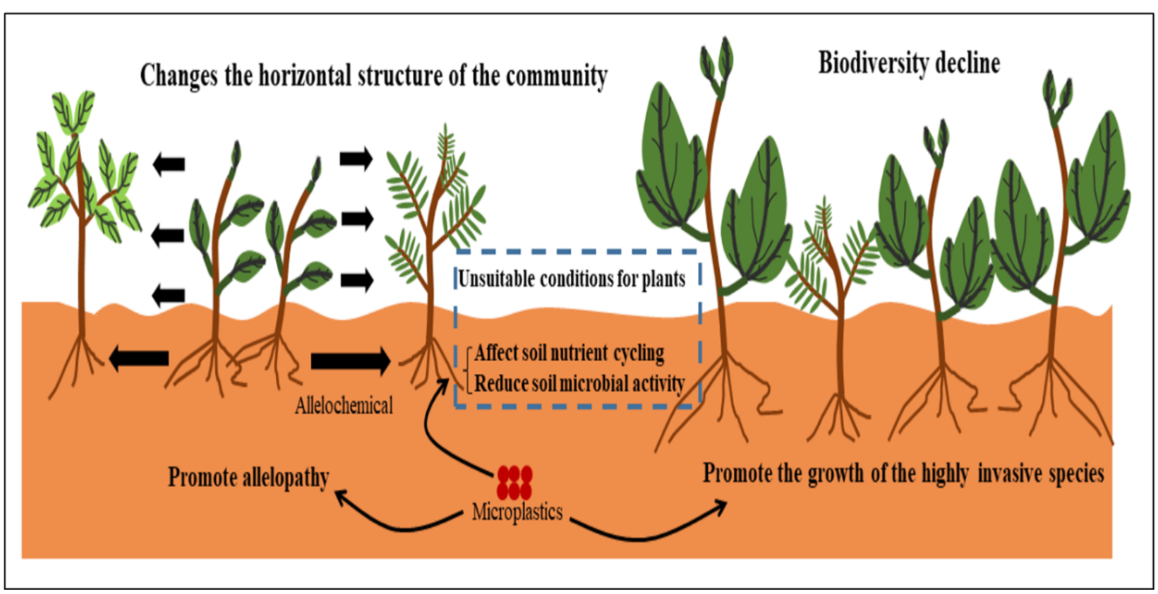

Fig. 3. Effects of microplastics on plant community structure.

structure of the community may also be affected by microplastic pollution due to the various potential effects of microplastics on several plant species under different conditions.

4.3. Potential consequences for ecosystem functioning

Community evenness, an important index of ecosystem function, refers to the distribution of the number of individuals of all species in a certain community, which reflects the evenness of the number of individuals belonging to each species. The experimental results of Lozano and Rillig (2020) suggest that microplastics can have a significant impact on the evenness of plant community biomass, which may further affect ecosystem function. Additionally, microplastics can further potentially modify community evenness through species abundance or survival (Balvanera et al., 2005; Hillebrand et al., 2008). Moreover, in communities dominated by species that are highly resistant or resilient to disturbance, a change in the relative abundance of plants could affect the ecosystem's own resistance and resilience.

Microplastics can also potentially affect plant communities by influencing nutrient cycling and microbial decomposition (Prambauer et al., 2019; Zhang et al., 2017). For example, Iqbal et al. (2020) found that microplastic pollution can have significant negative effects on the soil's N cycle. Soil incorporation of microplastics was associated with repressing the activity of key N cycling enzymes, including leucine aminopeptidase and N-acetyl-β-glucosaminidase, indicating potential implications for N availability in the soil. Additionally, litter decomposition is a key process for carbon and nutrient cycling, and the yield and quality of litter vary with relative plant richness (Tiwari et al., 2020). Microplastics can affect the decomposition of litter by affecting soil properties such as aggregate stability, aeration, and water content through decomposing enzymes and soil carbon storage (Leifheit et al., 2021).

Currently, the impact of microplastic pollutants on ecosystem function is not fully understood; however, researcher has identified a number of potential associated ecological risks, and their effects on ecosystem functioning should be a high priority for future research (Browne et al., 2007).

5. Effects of microplastics pollution in plant communities on agroecosystems and human health risk

The pollution of microplastics in plant communities has caused great pressure on the ecological environment, especially for agricultural ecosystems (Machado et al., 2018). Ng et al. (2018) estimated the maximum load of microplastics in agroecosystems in Europe, North America and Australia, and found that the load of microplastics from organic waste recycling alone was as high as $2.8 \sim 63$ t $\cdot hm^{-2}$. Among these, the addition of organic wastes (e.g., compost and biosolids) that may be contaminated by plastic and the use of plastic mulch are the main ways that microplastics enter agroecosystems (Zang et al., 2020). Iqbal et al. (2020)'s studies have shown that microplastics in agroecosystem can not only reduce soil microbial biomass, microbial activity and functional diversity, but also affect the cycle of plant nutrient elements in soil. Thus, the negative effects of microplastics on plant communities are more likely to occur in agricultural fields with high microplastic pressure.

The accumulation of microplastics in crops could pose a potential human health risk. Enrichment and transmission in the food chain is an important way for microplastics to be exposed to human body. Li et al. (2019) found that lettuce could absorb and accumulate polystyrene microspheres (0.2 μm) under the condition of nutrient solution hydroponics and transport them to the stem and leaves that could be eaten directly. Researcher has speculated that after entering the human body, microplastic particles can be broken down into smaller particles and enter the human organs through the circulation system (Rainieri et al., 2018). Exposure to microplastics can cause various kinds of biological and human cells to appear different degrees of oxidative stress reaction (Kelly and Fussell, 2012; Valavanidis et al., 2013). When the amount of reactive oxygen in the body increases, it causes inflammation. For example, wear of plastic prosthetic implants releases large amounts of microplastics. PE and PET wear particles have been observed in the joint capsule, lumen, and surrounding tissues of patients treated with plastic stents (Wright and Kelly, 2017). A handful of scientific papers have linked microplastic particles to diseases such as dermatitis, respiratory infections and cancer in certain oral pathways (Prata et al., 2020).

6. Conclusions and prospects

Microplastics are emerging pollutants that have received increasing attention. By summarizing past experiments, we provide a good overview of the effects of microplastics on plant communities. Microplastics in terrestrial systems can affect plant communities in multiple ways. Since the absorption of microplastics by plant roots is the principal mode of entry into plant bodies, soil pollution is the main cause of invasion of microplastics to plant communities. The effects of microplastics on plant communities are mainly reflected in the community biomass, structure and ecosystem function. The influence of microplastics on the community biomass is affected by many factors and varied under different conditions. In terms of community structure, microplastics affect community level distribution through its effects on the soil physicochemical properties and allelopathic effects, and influence community biodiversity by promoting the growth of invasive species. In addition, microplastics can also have potential impacts on ecosystem functions by affecting the evenness of community organisms, nutrient cycling in soil systems, and microbial activities.

Heretofore, most relevant experiments have been carried out in laboratory conditions, where the individual plants were studied, the exposure time was relatively short, and the microplastic concentrations used was higher than those found in the environment. Therefore, it is necessary to comprehensively evaluate the effects of microplastics based on actual environmental characteristics. Additionally, most of the experimental objects of current studies are herbaceous plant communities, and research on more complex woody plant communities is still lacking. Future research on this topic should include these communities and start to conduct long-term experiments.

Author statement

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Declaration of Competing Interest

No conflict of interest exits in the submission of this manuscript, and manuscript is approved by all authors for publication. I would like to declare on behalf of my co-authors that the work described was original research that has not been published previously, and not under consideration for publication elsewhere, in whole or in part. All the authors listed have approved the manuscript that is enclosed.

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