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Can microplastics mediate soil properties, plant growth and carbon/nitrogen turnover in the terrestrial ecosystem?

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ABSTRACT
Microplastic (MP) pollution, a global environmental problem, has been recently studied in marine and freshwater environments. However, our understanding of MP effect on terrestrial ecosystems, especially carbon (C) and nitrogen (N) turnover remains poor. This review summarizes the sources and distribution characteristics of MPs in terrestrial ecosystems and explores their effects on soil properties, plant growth, C and N turnover. Once entering the terrestrial ecosystem, MPs could involve in sequestrating carbon and nitrogen by changing soil properties (e.g., pH, soil aggregate stability, and soil porosity). MPs could exert direct influences on plants or on soil physical environment and microbial metabolic environment to indirectly affect plant growth, thus altering the quantity and quality of soil C and N inputs by shifts in plant litter and roots. The changes of the dominant bacteria phyla, related functional genes, and enzymes caused by MP pollution could affect C and N cycles. Additionally, the MP effect varies with its properties (e.g., types, shapes, elemental composition, functional groups, released additives). Future researches should unify the standard system of MP separation, detection, and reveal the ecological effects of MPs, especially their impacts on terrestrial carbon and nitrogen cycles in the context of climate changes.

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Introduction

Microplastics (MPs) was plastic particles of size less than 5 mm, originating from massive use and improper disposal of plastics (Cole et al. 2011; Zang et al. 2020). Based on formation process, they could be divided into two categories: primary MPs (Wiedner and Polifka 2020) and secondary MPs (Weithmann et al. 2018; Kumar et al. 2020). The serious MP pollution in the aquatic ecosystem has been widely reported,while the terrestrial ecosystems were larger MP sink (Andrady 2011), with less attention. Until 2012, German scientist Rillig reported the presence of MPs in soil (Rillig 2012), then substantially increased reports began to focus on MPs in terrestrial ecosystems. They found that MPs can enrich metal pollutants, release certain additives and affect soil properties, microbial communities, animal toxicological properties, and plant growth (Law and Thompson 2014; Hou et al. 2020; Yang et al. 2021). Wind, precipitation, plant roots growth, soil animals consumption, excretion, and peristalsis, human activities, such as tillage, weeding, and harvesting could affect the process of MP migration and translation laterally and vertically (Li et al. 2021a; Yang et al. 2021). Precipitation and irrigation leads to the upward movement of MPs due to its small density (Li et al. 2021a), while MPs could also move downward due to the ecocorona formed by microbial colonization and nutrients and organic pollutants absorption on the MP surface (Galloway, Cole, and Lewis 2017; Santana-Viera et al. 2021). Furthermore, under the presence of ultraviolet radiation, weathering, animals, and microorganisms, MPs in soil environment is further fragmented, and transformed into nanoplastics (NPs) with size less than 1 μm (Li et al. 2021b). Although plenty of studies have shown gradual accumulation of MPs in the terrestrial ecosystems, the knowledge of their potential interactions is still poor.

Carbon and nitrogen turnover in the terrestrial ecosystem is mainly a process of migration and transformation between vegetation and internal components of soil and between the atmosphere and water environment (Yu et al. 2014). Abiotic factors such as soil physical and chemical properties, climate, and topography, as well as biological factors such as vegetation, microorganisms, animals, and human activities affect the terrestrial ecosystem's complex carbon and nitrogen turnover process (Zhu and Wang 2019; Chen et al. 2020b; Wang et al. 2020d).

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MPs are composed of carbon and other elements and can be imported into terrestrial ecosystems as carbon sources independent of photosynthesis and primary productivity (Rillig and Lehmann 2020). Plastics can be broken down by living and non-living things, producing smaller pieces and greenhouse gases suspended in the air (Rochman and Hoellein 2020). Although turnover of these carbon source in the ecosystem is slow, they can indirectly impact the carbon and nitrogen cycle of the terrestrial ecosystem by affecting soil physical and chemical properties and microbial processes (Rillig and Lehmann 2020). This paper reviews MP source and distribution characteristics in the terrestrial ecosystem, the effects of MPs on soil physical and chemical properties, plant physiological state, microbial community composition and diversity, and also soil enzyme activity. We summarize the influence of MPs on carbon and nitrogen turnover in the terrestrial ecosystem and its related mechanism. This, in turn, is expected to provide references for the ecological effect of MPs and their impact on the carbon and nitrogen cycle in the terrestrial ecosystem.

Literature retrieval

Due to wide distribution, MPs, especially MPs in soil have been the hotspot in recent studies (Figure 1a). The keywords "microplastics" individually, "microplastics" combines with "terrestrial ecosystem," "soil," "land," "plant," "microorganisms," "carbon," "nitrogen" were used to retrieve literatures on Web of Science and Google Scholar. There were no restrictions in title, abstract, publication date, study location. The literatures published from 2016 to 2021 were regarded as the major in the subsequent assimilation and analysis. The number of publications containing the keywords "microplastics" conjuncted with "soil properties," "plant," "microorganism" increased year by year, but there were few studies on the effects of microplastics on carbon and nitrogen turnover (Figure 1b).

Distribution characteristics and sources of MPs in the terrestrial ecosystem

MP pollution in the terrestrial ecosystem is 4–23 times higher than that in aquatic ecosystems, serving as a more prominent recipient (Horton et al. 2017a, 2017b). The sources are mainly agricultural film mulching and sludge application. In Europe and North America, more than 7 million tons of MPs are input into the agricultural soil every year (Nizzetto, Futter, and Langaas 2016). Weithmann et al. (2018) estimated that 35 billion to 2.2 trillion MPs enters crop soil through compost application in Germany each year. The MP content of topsoil in industrial areas around Sydney and farmland near roads was as high as 7%, the highest in all existing publications (Fuller and Gautam 2016). Corradini et al. (2021) found that the abundance of MPs in farmland and pasture in the Chilean valley was 306 ± 360 and 184 ± 266 particles/kg. However, no MP pollution was found in natural grassland dominated by shrubs, showing that the MP pollution in farmland soil was often higher than other ecosystems (Corradini et al. 2021). The agricultural soil MPs in Korea were mainly PE, PP, and PET. The use of plastic products in agricultural production was a major cause of farmland MP pollution (Kim et al. 2021). Similarly, MPs are widely present in the terrestrial ecosystems of China. The abundance of MPs in facility agricultural soil and open field agricultural soil in Shouguang, Shandong, which is the most extensive greenhouse vegetable production base in China, was 310–5,698 particles/kg (Yu et al. 2021). MPs with smaller particle sizes tend to migrate to deeper soil layers

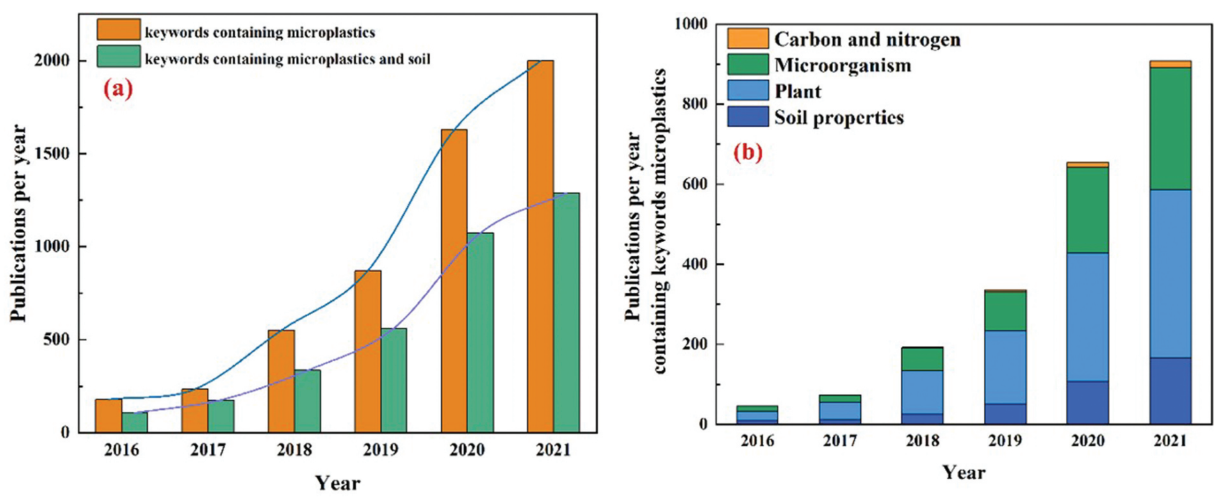

Figure 1. (a) Literatures per year containing the keywords "microplastics," "microplastics and soil" on indexed journals between 2016 and 2021. (b) Literatures per year containing the keywords "microplastics" conjuncted with "soil properties," "plant," "microorganism," "carbon and nitrogen" on indexed journals between 2016 and 2021. Data sourced from web of science.

(Yu et al. 2021). The concentration of MP particles in vegetable soil in Wuhan of China reached 620,000 particles/kg. Agricultural film mulching and sludge application are the main sources of MP accumulation in this region's agroecosystem (Zhou, Liu, and Wang 2019). Huang et al. (2021) investigated 10 counties in Yunnan, finding that the distribution range of MP abundance in Yunnan Province was 9,000–408,000 particles/kg and the MP abundance of inland soil was one order of magnitude higher than that of offshore sediments, mainly due to long-term residue of the plastic cover. MP contamination in farmland soil is affected by many factors, of which human intervention is one of the most significant reasons for soil MP accumulation. Figure 2 shows the distribution characteristics of MPs in terrestrial ecosystems on a global scale, which shows divergent differences in MP distribution among various geographic locations.

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Overall, compared with natural earth, farmland soil has a higher content of MPs ranging from a few particles/kg to tens of thousands of particles/kg, mainly due to its abundant pollution sources. The shapes of MPs are primarily fiber, debris, and film, indicating that human activities, including agricultural and industrial activities, are critical sources of MPs in the farmland ecosystem. Polymer types and MP shapes can explain various MP sources to a certain extent. For example, PE, HDPE, and PP are commonly used in plastic packaging, woven bags, and agricultural films. PVC and HDPE are widely used for pipes in irrigation systems; films mainly come from packaging, industrial, and farming materials; fibers, which enter the terrestrial ecosystem through sewage runoff and sludge application, mainly come from clothes, curtains, and other textile products or fishery; fragments are usually broken down from large plastics; small spherical MPs mainly come from personal care products in sewage sludge (Brahney et al. 2020; Ding et al. 2020; Xu et al. 2021). Different soil types and their diverse physicochemical properties, especially pH, exchangeable mineral content (Kim et al. 2021), and land-use patterns, lead to differences in the abundance of MPs in various studies (Yu et al. 2021). Weather and climate can affect the decomposition of macroplastics and increase the abundance of MPs in soil. In addition, altitude, population density, precipitation, and local industry can also influence the distribution of MPs (Zhou et al. 2021b). Since related research on MPs is still in its infancy, there is a lack of unified methods and standards for extraction, quantification, and characterization of MPs. The differences in

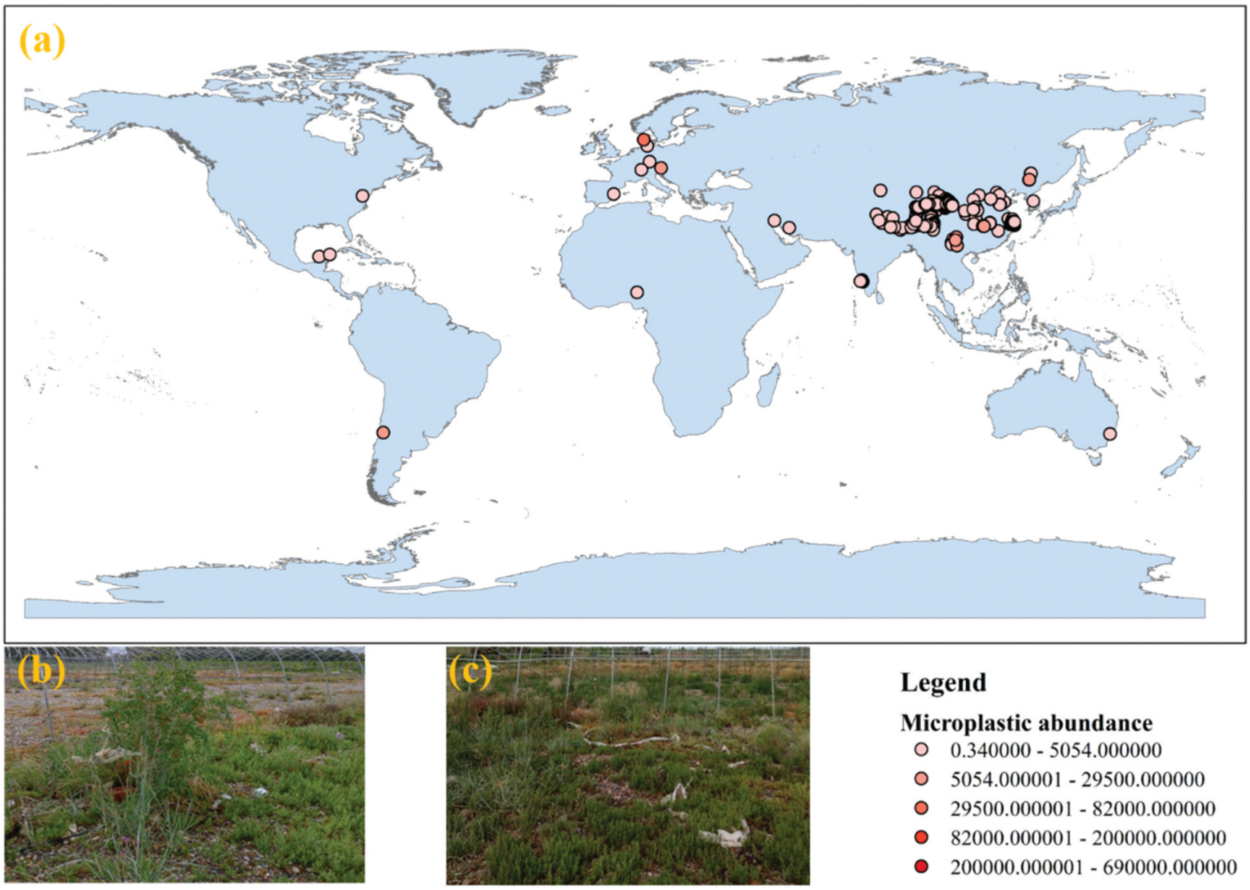

Figure 2. MP distribution in terrestrial ecosystems.

sampling time, sampling depth, and sampling-analysis methods are also cause for poor results (Li, Song, and Cai 2020a). Moreover, it is difficult to distinguish which factors are dominant due to the openness and complexity of the terrestrial ecosystem and the interaction among various environmental factors. Further exploration on the migration and transformation of MPs in soil is necessary to reveal the relevant mechanism.

Effect of MPs on soil physicochemical properties

MPs can affect the physical and chemical properties of soil aggregates, pH, electrical conductivity, and bulk density, with varying results, depending on the MP type, particle size, morphology, and soil types.

Effect of MPs on soil aggregates

Soil aggregates are formed by the mutual cementation of soil particles and organic matter. Their formation and stability result from a combination of soil physics, chemistry, and biology (Bronick and Lal 2005). According to the classification theory of aggregates, those with a diameter greater than 0.25 mm are macro aggregates and are divided into stable water and non-water stable aggregates. Those with a diameter of less than 0.25 mm are micro aggregates (Tisdall and OADES 1982). Soil aggregates have multilevel porosity, which can coordinate the contradiction between water, gas, and heat in the soil, maintain organic matter, and regulate the supply of nutrients (Zhang and Zhang 2020). C and N in macro aggregates are mainly physical protection, mostly from plants, and have fast turnover speed, while C and N in micro aggregates are mainly chemically protected, mostly from microorganisms, have low turnover speed (Paul et al. 2013). Research about the influence of MPs on soil aggregates currently focuses on the number of water-stable aggregates and newly formed aggregates, the size of aggregates, the average weight diameter of aggregates, and so on. Among these, the effects of MPs on the stability of aggregates are different. Machado et al. (2018) revealed an average diameter of 18 μm acrylic microfiber (PMMA) decreased the number of soil water-stable aggregates, while the polyester microfiber (PES) with 8 μm diameter had the opposite effects. A pot culture test of welsh onion in 2019 found polyamide (PA), PES, and PS treatment reduced the number of water-stable aggregates (Machado et al. 2019). The contrasting results of these experiments may be due to the difference in MP addition gradient and the types of crops planted. Adding high-density polyethylene (HDPE) and polylactic acid (PLA) MPs to red ryegrass soil can reduce the number of large aggregates and change the structure of stable water aggregates. MPs promote the combination of MPs and soil matrix by affecting the feeding activities of earthworms and other soil-eating animals. Meanwhile, MPs may change the bonding mode between micro aggregates, thereby reducing the formation of large aggregates (Boots, Russell, and Green 2019).

Through meta-analysis, Lehmann et al. (2020b) found the linear structure of PES microfibers harmed the stability of soil aggregates and large aggregates. On the contrary, a pot experiment (Lehmann et al. 2020b) found that MP beads reduced the formation of soil aggregates but increased the stability of aggregates. In this pot experiment, it might be probably because the small particle size of MP beads was unable to be combined with smaller aggregates, while foamed MP adversely affected the formation and stability of aggregates. Plastic debris harmed the construction of aggregates but had no apparent effect on aggregate stability. Therefore, the influence of MPs on the properties of soil aggregates depends on their shape. Similarly, Zhao et al. (2021) found that MPs can reduce the formation of large aggregates and the number of water-stable aggregates as well as the average weight diameter of aggregates could be reduced by PES microfiber (Lehmann et al. 2020a). Meanwhile, some studies have shown that the influence of polyester microfiber on stable water aggregates depends on the type of organic matter, which is an important factor affecting soil agglomeration. Therefore, the number of MPs entering the aggregates is also affected by the kind of organic matter, aggregates containing MPs tend to have low stability (Liang et al. 2021). In general, MPs mostly have adverse effects on the formation of large soil aggregates and water-stable aggregates. Still, the effects varies with the shape, soil structure, and type of MPs. Compared with film and microbead MPs, fibrous MPs have more significant effects on soil aggregates (Lehmann et al. 2020a).

Effect of MPs on other soil physicochemical properties

Soil bulk density refers to the ratio of soil per unit volume (including soil particles and pores between particles) after drying to that before drying and is an essential physical property of soil (Wang et al. 2020c). With a smaller bulk density, soil structure is relatively loose and has a higher water and fertilizer storage capacity, which is conducive to plant growth (Liu et al. 2020). Compared with soil particles, the density of MPs was lighter, which often reduced the soil bulk density (Machado et al. 2018, 2019). However, some studies found no significant effect of PES microfiber on soil bulk density, probably due to the low quality of PES microfiber (≤0.3%) (Zhang, Zhang, and Li 2019).

pH is a critical factor determining soil nutrient mobility and plant nutrient uptake. MP occurrence affected soil pH, but this influence depended on MP type and its concentration. A pot experiment found that soil pH of farmland in Qingdao, Shandong Province, increased with the increase of PLA, while PE decreased soil pH. The different effects of PLA and PE may be due to their diverse biodegradation characteristics in soil systems (Wang et al. 2020b). Qi et al. (2020)found that low-density polyethylene (LDPE) and PLA MPs reduced soil pH. Similarly, PE can lower the pH in different aggregates (>250 μm, 53–250 μm, <53 μm) (Hou et al. 2021). MPs disrupted the original aggregate structure of soil aggregates, resulting in a weaker adsorption capacity of cations on the surface of soil colloids, therefore reducing soil pH (Hou et al. 2021). Moreover, MPs can also significantly enhance water evaporation rate by establishing water flow channels, resulting in soil drying (Wan et al. 2019). For example, Koskei et al. (2021) showed that LDPE and biodegradable plastic film residues negatively affected evapotranspiration, water use efficiency, and soil porosity.

Overall, soil physical and chemical properties are essential to the process of soil carbon and nitrogen turnover. On the one hand, MPs could directly affect the ability of soil to immobilize carbon and nitrogen by altering soil physical and chemical property. On the other hand, MPs could indirectly affect plant growth, microbial community structure and activity by changing soil physical and chemical properties, and then affect the process of soil carbon and nitrogen turnover.

Effect of MPs on plant growth

MPs can influence vegetation carbon pools by affecting plant growth, so as to alter carbon and nitrogen turnover in terrestrial ecosystems. An experiment with 10% PLA addition showed a reduction in maize biomass and chlorophyll content in leaves, while PE had no significant effect (Wang et al. 2020b). This may be caused by the different biodegradation characteristics of the two MPs in soil. PLA is a biodegradable plastic, while PE is a petroleum-based plastic with a slow degradation rate. PLA and its intermediate metabolites may directly or indirectly affect plant growth by changing the structural properties of soil and microbial communities. Qi (Qi et al. 2018, 2020) found that PLA had a more significant effect on wheat growth than PE. The addition of the biodegradable plastic intermediate polyhydroxybutyrate valerate copolyester (PHBV) for four weeks resulted in the death of wheat plants, mortality was due to bio-based MPs consisting of C, H, O, and the lack of N, P, and other nutrient elements required for plant growth (Zhou et al. 2021a).

Studies proved PE, LDPE, and PLA negatively affected the root growth of maize at all growth stages and reduced biomass accumulation of maize roots and buds, possibly due to the inhibition of root growth and consequent water and nutrient uptake by root systems (Hu et al. 2020; Koskei et al. 2021). Similarly, MPs also inhibit ryegrass germination rate and biomass (Boots, Russell, and Green 2019), watercress germination rate and root growth (Bosker et al. 2019), rice seedlings (Dong et al. 2020) and kidney beans growth (Meng et al. 2021). Li et al. (2021c) found that MP occurrence induced an oxidative stress response of wheat and scavenged the excess reactive oxygen species (ROS) through the ascorbic acid glutathione (ASA-GSH) cycle. In addition, it also inhibited sucrose degradation by reducing the activities of sucrose synthase and sucrose invertase, promoting starch accumulation by increasing the activity of glucose pyrophosphorylase (AGPase). MPs blocked root pores, inhibited root growth, deposited in the angiosperm seed coat, and inhibited water absorption, thus delaying seed germination (Bosker et al. 2019). By indoor culture experiments, Li et al. (2019) found that MPs were intensely absorbed and enriched in significant quantities by lettuce roots, migrated to the aboveground, and then accumulated in stems and leaves.

Other studies found that nano plastics with smaller particle sizes entered tobacco cells through endocytosis (Bandmann et al. 2012). MPs can enter plants through the gaps formed during the growth of lateral plant roots (Li et al. 2020b). However, Lehmann et al. (2020a) found that PE microfibers promoted the growth and development of onion plants and their roots, possibly because microfibers improved soil air permeability and water-holding capacity by reducing soil bulk density to promote onion growth.

Different types and concentrations of plastics have diverse effects on the growth of various plants MPs have adverse effects on the germination and growth of most plants, and degradable plastics have a more significant impact. The result of MPs and plasticizers and their additives from the aging process on plants can disturb the absorption of water and nutrients by affecting soil structure, physical and chemical properties, and microbial community, inhibiting or promoting plant growth. MPs can adhere to plant roots or seed coats and directly affect plant growth; complex roots can trap MPs through the root systems or secretions, resulting in an increased abundance of MPs in the soil. In addition, MPs with smaller particle sizes can be directly absorbed and enriched by plants, which can migrate with the food chain and even affect human health.

Effect of MPs on soil microorganisms

Effect of MPs on soil bacteria and fungi

Soil microorganisms are crucial components of the terrestrial ecosystem (Zhang and Liu 2001). They drive soil carbon, nitrogen, and phosphorus cycles, regulate greenhouse gas production and emission as well as other ecological processes, closely related to soil health and crop production (Zhang et al. 2020). The influence of MPs on microorganisms can be summarized into three aspects: Firstly, MPs can provide attachment carriers for microorganisms; Secondly, plasticizers and additives released by MPs in soil affect microbial community structure and abundance; and thirdly, MPs affect microorganisms by altering soil structure and properties. A report in Science indicates that photothermal degradation of microplastics can produce soluble organic compounds that promote or inhibit microbial growth (Stubbins et al. 2021). Miao et al. (2019) found that compared with natural substrates such as pebbles and short wood, MPs were unique habitats for microorganisms and changed community structure and abundance. Rong et al. (2021) found that 2% and 7% concentrations of LDPE slightly reduced Shannon diversity index but increased the relative abundance of actinomycetes which could degrade lignocellulose and degradable MPs (Abraham et al. 2017). Low-dose MP addition improved the quantity of Proteus and Bacteroidetes. Due to its metabolic diversity, proteus plays a vital role in the terrestrial carbon, nitrogen, and sulfur cycles. Bacteroidetes are more abundant in soils with high soil organic carbon content, related to degrade complex soil organic matter (Spain, Krumholz, and Elshahed 2009). The metabolism of both nitrogenous compounds and carbohydrates was enhanced by increasing the relative abundance of Proteus and Bacteroides (Cebron et al. 2008).

The effects of MPs on microorganisms were diverse, with different experimental conditions and types of polymers causing various effects. LDPE significantly changed the structure of soil bacterial community, promoted continuous succession of the microbial community (Wang et al. 2020a), as well as increased the total bacterial abundance and decreased the bacteria α diversity (Gao et al. 2021). The same effect also was found in PVC and PE MP (Zang et al. 2020), which can increase microbial biomass, shift dominant bacteria from gram-positive to gram-negative bacteria, and then stimulate soil carbon cycle. Particle size may be one of the drivers affecting microbial community and those with larger particle size increased microbial Shannon diversity index and changed microbial community structure (Ren et al. 2020). Moreover, the relative abundance of rhizosphere bacteria in wheat treated with different MPs was diverse at the phylum level (Qi et al. 2020). Still, proteus was dominant, followed by actinobacteria and acid bacteria; PLA had a more significant impact on the composition of the bacterial community than LDPE (Qi et al. 2020). However, there are also researches with different views. LDPE had no significant effect on the diversity of the soil microbial community (Huang et al. 2019). The variety of microbial communities on MPs was significantly lower than that of soil itself, but enriched the actinomycetes (Huang et al. 2019). PE and PVC reduced the richness and diversity of the bacterial community, induced the functional response of membrane transporter proteins, and maintained homeostasis on the transporter protein's synthesis and activity (Fei et al. 2020). MPs were selective in their effects on microorganisms and may significantly affect the abundance of specific bacterial populations (Yan et al. 2020). Previous studies about MPs on microorganisms primarily focused on farmland ecosystems. Aging LDPE and PET also reduced the diversity and evenness of forest soil microbial communities and changed the community composition, and the effects of these two MPs were different (Ng et al. 2021). Rillig put forward an innovative view that the impact of MPs on soil properties puts certain selection pressure on soil biota, resulting in population genotype changes, either through mutation or selection in existing genes, with the result showing that microorganisms able to utilize carbon and other elements in MPs have more advantages (Rillig et al. 2019). Another interesting finding is that microbes can pick up carbon atoms in MPs to form cell membranes (Rochman and Hoellein 2020).

Fungi are another essential component to soil microorganisms, and the number and species of fungi vary in aggregates with different particle sizes. There are few studies on the effects of MPs on soil fungi. Hou et al. (2021) found that PE reduced the abundance of fungi in large aggregates, but a change of <53 μM fungi in aggregates was not obvious and did not change the Ascomycetes trend dominant bacteria. A structural equation model found a correlation between fungi and soil physical and chemical properties and enzyme activity (Hou et al. 2021). In addition, researchers also isolated a series of bacteria/fungi that can degrade MPs in sewage sludge, landfills, animal intestines, and other places. Different bacterial species can degrade traditional plastic polymers, such as Streptomyces, Rhodococcus, and Nocardia for PE MP, and Pseudomonas and Bacillus for PS MPs (Maity et al. 2021).

Effect of MPs on soil enzyme activity

Soil enzymes are released from animal and plant residues and decompositions as well as the secretion of soil microorganisms and plant roots, and mainly include oxidoreductase, hydrolase, transferase, isomerase, lyase, ligase (Xu et al. 2004). Soil enzymes are involved in soil biochemistry, energy transfer, nutrient cycling, environmental quality, organic matter decomposition, and other processes (Wan and Song 2009). Different soil enzymes act differently. Urease, phosphomonoesterase, and invertase activities, respectively, characterize the ecological function of soil microorganisms participating in soil C, N, and P cycles (Bian et al. 2016). Soil dehydrogenase exists in living cells and its activity is positively correlated with the number of microorganisms and the content of organic matter (West et al. 2006). β-glucosidase is an extracellular enzyme that plays a vital role in the carbon cycle by producing glucose, an important energy source for microorganisms (Hibbing et al. 2010). Fluorescein diacetate hydrolase represents metabolic activity and indicates soil vitality and the intensity of microbial activity (Perucci 1992). Phenol oxidase is involved in the degradation of stubborn phenols such as lignin (Keuskamp et al. 2015).

Researches showed that PP could increase the activity of fluorescein diacetate hydrolase, thus increasing the hydrolysis activity of microorganisms to organic matter and accumulating soil organic matter (Liu et al. 2017). It increased phenoloxidase activity on the 7th and 14th days and led to the dissolution of high molecular organic matter (Liu et al. 2017). Through a microcosm experiment, Fei et al. (2020) found that PVC and PE significantly increased soil urease and acid phosphatase activities and reduced the activity of fluorescein diacetate hydrolase.

PE has a more significant impact on urease activity, and PVC has a greater effect on acid phosphatase activity. The change of enzyme activity was mainly affected by moisture and microbial community. However, Chen et al. (2020a) reported different result, and found that adding 2% PLA had no significant effect on β- Glucosidase, catalase, urease, and microbial activities. The impact of 2% PLA MPs on soil physical and chemical properties was not sufficient to change soil bacterial diversity and its mediated biological processes. Moreover, it could be possible that soil itself had the ability of self-purification and maintained homeostasis against external disturbance. An incubation experiment found that PE significantly inhibited the activities of catalase, polyphenol oxidase, and urease in different aggregate fractions and have the most noticeable inhibitory effect on urease in large aggregates and polyphenol oxidase in micro aggregates (Hou et al. 2021). Similarly, the inhabitations of PE on activities of soil catalase, urease, manganese oxide enzyme, lactate dehydrogenase, and glutamate, were mainly from of the reduction of soil organic carbon, nitrogen, phosphorus, and other nutrients induced by MPs (Yu et al. 2020). However, Guo et al. (2021) found that PES microfibers increased soil laccase and cellulase activities, probably due to their similar chemical structure and enzyme-substrate.

This study summarized that the effects of MPs on soil enzyme activity include direct and indirect effects. Some specific MP structures may be similar to enzyme substrates, promoting soil enzyme activity and degradation, while other MPs can compete with microorganisms for physical and chemical niches and reduce microbial activity to reduce enzyme activity. Additionally, different enzymes have different activities under various environmental conditions. The effect of MPs can also indirectly affect soil enzyme activity by changing soil physical and chemical properties.

Effects of MPs on carbon and nitrogen turnover in the terrestrial ecosystem and its mechanisms

At present, there are few studies on carbon and nitrogen turnover and greenhouse gas emission of the terrestrial ecosystem, as affected by MPs. However, existing studies show that MPs could affect the carbon and nitrogen turnover in the terrestrial ecosystem. The impact of MPs on the carbon and nitrogen turnover process, greenhouse gas emission, and related mechanism are listed as follows:

Effect of MPs on carbon and nitrogen turnover

MPs may enter the soil with other organic substances from tillage practices as well as soil organisms and become unnatural sources of soil organic carbon (Rillig 2018). Science reported that MPs currently account for 0.1% of soil organic carbon (MacLeo et al. 2021). MPs can also indirectly affect carbon and nitrogen cycle process by affecting plant growth and soil environment. For example, MPs regulate carbon and nitrogen input of the terrestrial ecosystem by affecting the carbon pool of vegetation. MPs reduce the primary productivity of plants and reduce their fixation of carbon dioxide from the atmosphere by inhibiting their growth. Also, as shown in Figure 3, plant underground roots and litter are essential input sources of soil organic matter. MPs can change the input quantity and quality of soil organic carbon by varying soil nutrients and water status and then affecting plant biomass accumulation.

Although MPs are different from primary productivity and are inert carbon sources, studies have shown that some microorganisms can use MPs as carbon sources to degrade and release gases such as CO_2, which may be because microbes secrete hydrolases that break chemical bonds in MPs (Stubbins et al. 2021). Microbial activities in the terrestrial ecosystems are usually carbon limited, and even a tiny amount of carbon input will cause changes in the soil microbial

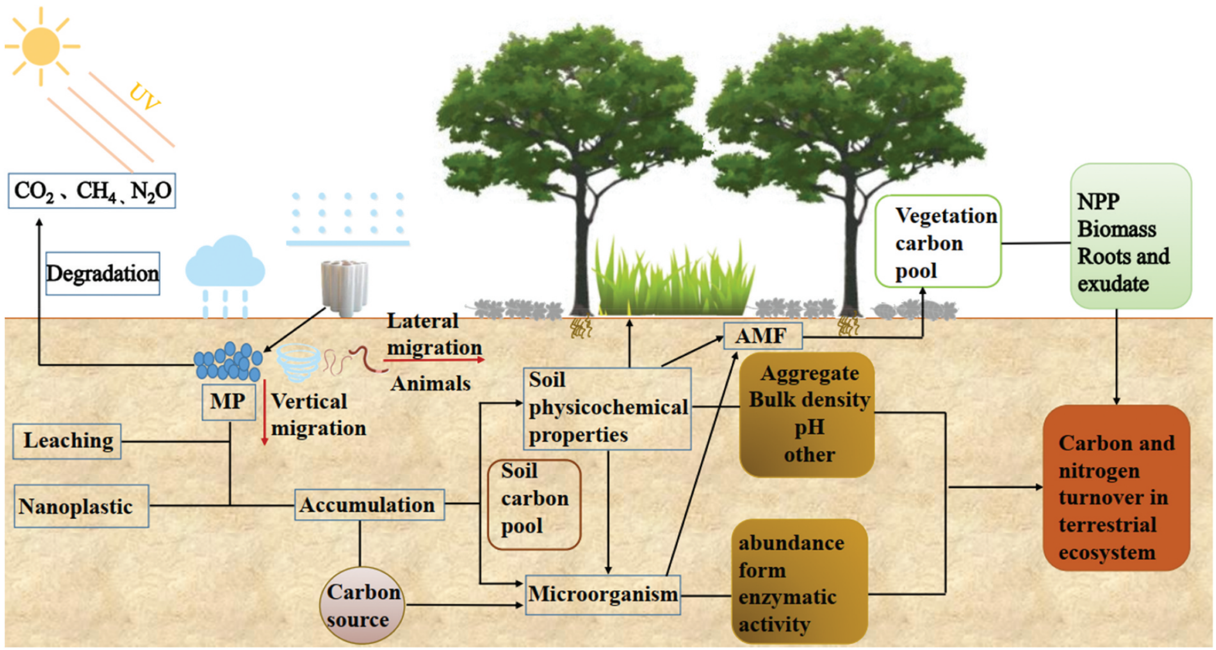

Figure 3. The fate and ecological effects of MPs on the terrestrial ecosystems.

community. PHBV increased microbial activity and external enzyme activity, leading to co-metabolism to enhance organic mineralization, accelerating carbon, and nutrient turnover in the microplastisphere (Zhou et al. 2021a). The prime effect refers to the phenomenon of increased organic matter loss from soil under the background of exogenously added substances, including apparent prime effect caused by microbial turnover and natural prime effect from organic matter decomposition (Zhang et al. 2021). The addition of MPs such as PE may affect the mineralization of soil organic matter through apparent excitation (Kuzyakov 2010). Rong et al. (2021) explored the effect of LDPE MPs on the soil nitrogen cycle through culture experiments. They found that the addition of MPs promoted the gene abundance of nifH, AOBamoA, nirK, and nirS and increased the chances of nitrogen cycle microbial genus abundance and community structure. The increase of nirK gene abundance may be due to the increase of denitrifying flora such as Pseudomonas, Streptomyces, and methylbacillus. MPs may serve as an organic carbon source for nifH gene bacteria (Seeley et al. 2020), promoting expression. Through a microcosm culture, it was found that the addition of LDPE in vegetable farmland significantly promoted carbon dioxide emission in the soil but did not affect nitrous oxide emission (Gao et al. 2021). However, some studies found that MPs led to the reduction of nitrous oxide emission and promoted the emission of carbon dioxide, and reported that more prominent MPs reduced the cumulative absorption of methane (Ren et al. 2020), possibly due to the different microbial activities of MPs affecting relevant carbon and nitrogen cycles resulting in inconsistent results.

The occurrence of PVC or PE could increase the relative abundance of nitrogen-fixing Burkholderia and Pseudomonas, which may increase biological nitrogen fixation and affect the nitrogen cycle of the terrestrial ecosystem (Fei et al. 2020). Ng et al. (2021) found that when 3% LDPE MPs were added, the daily CO_2 emission flux increased 7–8 times, although there was no significant difference in N_2O and CH_4 emission flux of forest soil. This is possibly due to the change of microbial community composition. Based on the isotope labeling method, Zang et al. (2020) found that MPs can significantly change the carbon turnover process in plant soil; the degree of impact is related to the type and abundance of MPs. The higher the abundance of PVC, the greater the CO_2 emission flux.

Through a pot experiment, Guo et al. (2021) found that PES microfiber promoted the degradation of soil organic matter. Microfiber not only provided a habitat for microorganisms, facilitating the acquisition of soil organic matter by microorganisms and increasing the activity of related enzymes, but also increased soil aeration, contributing to soil organic matter decomposition and accelerating soil carbon loss. Another field experiment on maize (Koskei et al. 2021) found that LDPE and biodegradable plastic film residues had no significant effect on soil organic carbon at all growth stages but increased soil total nitrogen content and decreased microbial biomass carbon (MBC) and microbial nitrogen (MBN), mainly due to the impact of MPs on the microbial community. MBC and MBN were closely related to total soil nitrogen and soil organic carbon mineralization (Liang and Zhu 2021).

Table 1. Impacts of MP on carbon and nitrogen turnover.

MP Type	Impact on C turnover	Impact on N turnover	Reference
PS	OC ↑		(Galgani et al. 2019)
PE		Urease that promotes hydrolysis of nitrogenous organic matter ↑	(Yi et al. 2021)
	CO_2 ↑ CH_4 ↓ as the particle size increases	N_2O ↓ (3d) N_2O ↑ (30d)	(Ren et al. 2020)
PP		Urease that promotes hydrolysis of nitrogenous organic matter ↑	(Yi et al. 2021)
	DOC ↑	TDN ↑ DON ↑ NO_3- ↑	(Liu et al. 2017)
LDPE		Nitrogen-fixing gene nifH ↑ Denitrification gene Nirk ↑ Ammonia oxidation gene AOB amoA ↑	(Rong et al. 2021)
		Urease that promotes hydrolysis of nitrogenous organic matter ↑	(Huang et al. 2019)
	SOC ↓	TN ↑	(Zhao et al. 2021)
	CO_2 ↑ DOC ↑	NH_4+ ↑ NO_3 ↓ Ammonia oxidation gene AOB amoA ↓ Denitrification gene Nirk ↓	(Gao et al. 2021)
PES	SOM ↓		(Guo et al. 2021)
PVC		NH_4+ ↑ NO_3–N, NO_2–N ↓ nitrogen-fixing gene nifDHK urea decomposersureABC genes and urease activity ↑ nitrate reducers genens nasA, NR, NIT-6 and napAB genes ↑ nitrifiers amoC gene ↓	(Ding et al. 2022)
		NH_4+ ↓ NO_3 – ↓	(Sun et al. 2022)
PET		NH_4+ ↓ NO_3 – ↓	(Sun et al. 2022)
PLA		NH_4+ ↓ NO_3–N, NO_2–N ↑	(Chen et al. 2020c)
	SOC ↓	TN ↑	(Zhao et al. 2021)
		NH_4+ ↓ NO_3 – ↓	(Sun et al. 2022)

Furthermore, the low concentration of MPs could cause microorganisms to form a "microplastisphere" conducive to the circulation of carbon and other elements, significantly accelerating soil organic matter decomposition. In contrast, higher concentration of MPs inhibited microbial activity, resulting in declining soil organic carbon utilization (Xiao et al. 2021).

Table 1 summarizes the recent research about the impact of MPs on carbon and nitrogen turnover. Related studies mainly focus on the effects of MPs on different forms of C and N concentration, greenhouse gas emissions, as well as functional microorganisms, enzymes, gene abundance and activity. It is interesting that most studies have found that MPs can contribute to CO_2 emissions, which may be attributed to the fact that most of the components of MPs are carbon elements. Also MPs have positive effect on soil DOC, possibly due to the ability of MP surfaces to leach (Romera-Castillo et al. 2018). Nitrification, denitrification, ammoniation, and nitrogen fixation are the key process in the soil nitrogen cycle. MPs could alter soil nitrogen content not only due to its elemental properties and functional groups, but also the change of key microbial genes and enzymes in the nitrogen cycle. Different types and abundance of MPs show diverse influences. Meanwhile, the difference of experimental time and ecosystem type could exert different effects. More in-depth studies are needed in the future, combined with proteomics and macrogenomic approaches.

Impacting mechanisms of MPs on carbon and nitrogen turnover in the terrestrial ecosystem

The first reason why MPs can affect the C and N cycle is their metabolic intermediates characteristics. MPs themselves can act as carbon sources to affect carbon and nitrogen turnover by influencing microbial processes. For example, MPs, 80% of which is carbon, can be used as carbon sources; also, almost 90% of PE and PS are carbon. Additionally, MPs have large specific surface areas, which affect the absorption of organic nitrogen and then inhibit the process of soil nitrification, denitrification, and ammoniation (Xia et al. 2017). It has also been reported that groups existing on the surface of MPs, such as hydroxyl and carboxyl groups, combine with ammonium nitrogen in the soil, which could reduce soil nitrogen availability (Zhou et al. 2021b). One recent study found that the surface of PA MPs formed persistent aminoxyl radicals and reactive nitrogen species after photoaging (Zhu et al. 2021). Moreover, MPs can cause the leaching of dissolved organic carbon by interacting with organic and inorganic matter or through microbial metabolism. Studies have shown that a high concentration nanoplastics can contribute to the total organic carbon value in water. However, their high chemical inertia will not participate in the biochemical reaction of organic compounds (Hu et al. 2019) (as shown in Figure 4).

Then, MPs can influence the carbon and nitrogen turnover process in the terrestrial ecosystem by affecting the physicochemical properties of soil. Soil organic matter is a crucial cementitious substance of soil aggregates (Zhang et al. 2015). MPs may reduce organic matter content in soil aggregates, mainly because MPs increase microbial respiration and soil organic carbon mineralization by disrupting the structure of the aggregates and weakening their ability to protect organic carbon, thus reducing soil organic carbon and increasing greenhouse gas emission flux (Zhao et al. 2021). Research shows that plastic

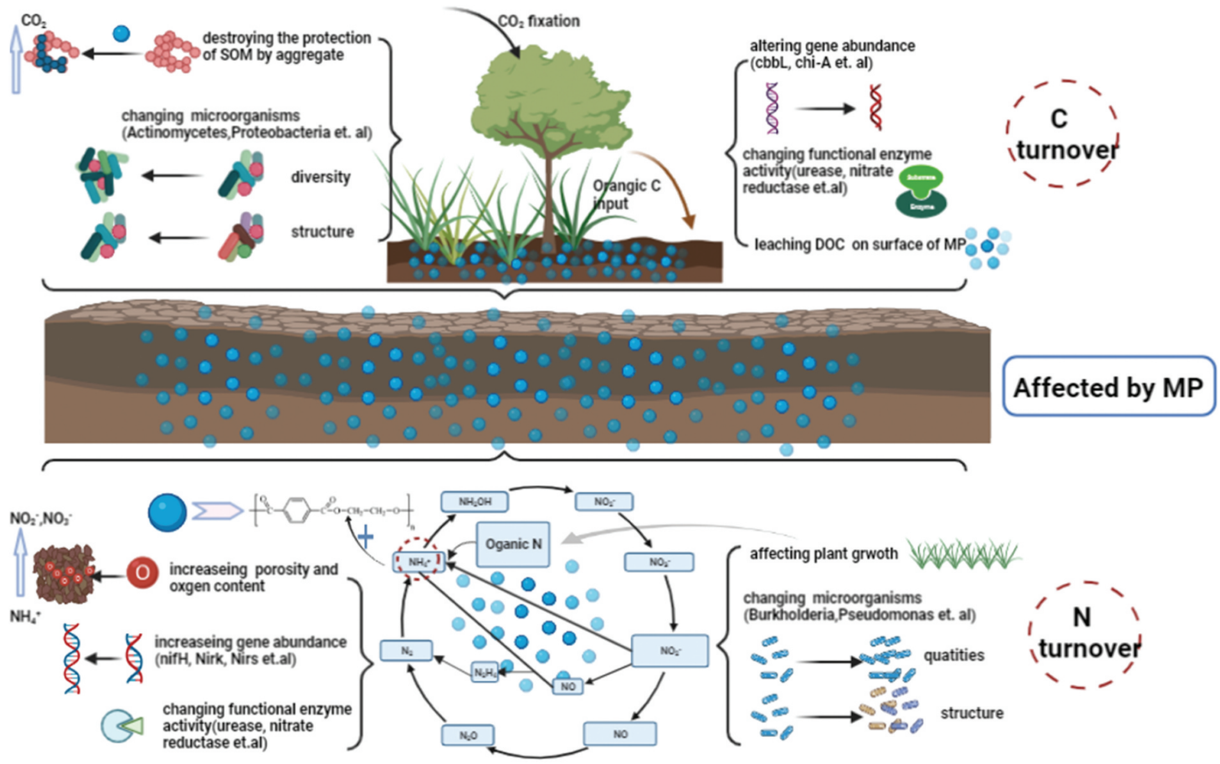

Figure 4. The connection between soil properties and C/N turnover as affected by MPs.

fragments increased the nitrogen content in soil aggregates, mainly because plastic fragments prevented the downward migration of soil water and soluble nitrogen and reduced nitrogen loss (Zhao et al. 2021). Some studies pointed out that MPs can increase soil porosity and oxygen diffusion, promoting nitrification (Chen et al. 2020a). 28% polypropylene significantly increased dissolved organic matter, indicating that high-level MPs promoted humus accumulation, mainly due to the change of PO enzyme activity (Liu et al. 2017). The more important is that the effects of MPs on soil physicochemical properties may be indirectly influence the plant growth, microbial composition, structure, soil enzyme activity, which were crucial to control carbon and nitrogen turnover, as shown in Figure 4.

MPs can also cause plant oxidative stress response by affecting the absorption of water and nutrients or direct accumulation in plants. They reduce the ability of plants to fix carbon dioxide from the atmosphere as well as reduce plant biomass and root exudates, thus affecting the input of vegetation to the soil carbon and nitrogen pool. MPs can directly affect the growth of arbuscular mycorrhizal (AMF) through their decomposition, releasing the adsorption of pollutants on the surface, or indirectly regulate the growth of AMF by affecting plant hosts, different root environments, and microorganisms, changing the carbon and nitrogen turnover rate and greenhouse gas emission flux of terrestrial ecosystem. Recent studies (Rillig and Lehmann 2020; Leifheit, Lehmann, and Rillig 2021) conjectured that MPs could lead to changes in the quantity and quality of root exudates by affecting primary productivity, increase the carbon content of roots, and change the carbon distribution of AMF, thus changing the carbon, nitrogen, and phosphorus cycle rate. AMF could stimulate microorganisms to decompose litter, enhance soil respiration, increase soil carbon loss and CO_2, and promote primary productivity. In addition, MPs can affect primary productivity by influencing plant growth. MPs can also promote nitrous oxide emission by increasing soil microbial activity (activating nitrogen in the soil). Therefore, MPs may change the role of AMF in the carbon and nitrogen cycle by affecting its activity, further influencing the carbon and nitrogen turnover rate in the terrestrial ecosystem (as shown in Figure 4).

Microorganisms play essential roles in carbon and nitrogen turnover in the terrestrial ecosystems by releasing carbon into the atmosphere through catabolism and converting exogenous carbon into substances for storage in the soil through anabolism (Liang and Zhu 2021). MPs can directly and indirectly affect microbial biomass carbon and nitrogen pool, and then affect the carbon and nitrogen turnover process of terrestrial ecosystems by influencing the composition and diversity of the related microbial community. Additionally, MPs could serve as carbon source to influence functional microbial activity, and then affect C/N turnover. MPs also could affect C/N turnover through microbial co-metabolism, apparent excitation, and alteration of related enzyme and gene activities. Different soil types and MPs have diverse effects (Mbachu et al. 2021), biodegradable plastics have a more significant impact. This may be due to the short culture experiment cycle; biodegradable plastics will degrade faster than that of inert petroleum-based plastics. The degradation and released intermediates of biodegradable plastics significantly impact the microbial community structure (Qi et al. 2020), thus affecting the carbon and nitrogen turnover process to a greater extent. For community composition, MPs can typically increase the abundance of degraded aromatic compounds, such as actinomycetes and Proteus (Ren et al. 2020; Rong et al. 2021), increasing the mineralization rate of soil organic matter and promoting the succession and evolution of microorganisms to populations that can use MPs (Gao et al. 2021). Meanwhile, MPs can provide carbon sources for certain microorganisms which have degradation effects, through either direct conversion into substances to produce energy or mineralization of carbon dioxide and water under aerobic conditions or methane and water under anaerobic conditions (Maity et al. 2021).

In addition, Rillig, Leifheit, and Lehmann (2021) proposed electron shuttling, microbial frustration, and positive and negative priming hypothesis to explain the impact of the interaction between MPs and soil microorganisms on the carbon cycle (as shown in Figure 5). The "electron shuttling" hypothesis holds that if microorganisms can obtain electrons from the weathered MP surface faster, both the transformation of soil organic matter and methane emission flux will be reduced. "Microbial frustration" hypothesis holds that MPs, and their additives, increase soil carbon molecular composition diversity and slow down the decomposition of soil organic matter. The hypothesis of the "negative priming effect" suggests that soil dissolved organic carbon may be adsorbed on the surface of MPs, resulting in the preferential metabolism of quickly mineralized organic carbon. The "positive priming effect" hypothesis holds that MPs and soil organic matter can be co-metabolized, mainly in additives and degradable MPs. However, no relevant research confirms these hypotheses. "Electron shuttling" holds negative priming effect which means the addition of exogenous organic matter inhibited the degradation of original organic matter. Meanwhile, DOC is the important part of SOM. The increased soil carbon molecular composition diversity means the more aromatic compounds in DOC, and the lower the bioavailability of microorganisms. Therefore, priming effect might be mediated by microbial frustration, as microbial activities influence DOC chemical characteristics, which consists of a variety of molecules ranging from simple acids and sugars to complex humic substances.

Moreover, soil organic carbon and total nitrogen are key factors of soil fertility, and the carbon and nitrogen turnover processes are intertwined. The turnover of carbon and nitrogen in soil is influenced by its measurement ratio (Chen et al. 2014), and soil properties involve in the relationship between carbon and nitrogen cycles in response to MP's occurrence. For example, MPs increased the quantity of Proteus and Bacteroidetes which could metabolize nitrogen compounds and carbohydrates (Cebron et al. 2008; Rong et al. 2021). Then, MPs could influence the quantity and quality of soil organic carbon and organic nitrogen inputs by affecting plant growth. MPs could alter the SOM content (Zang et al. 2020) at the same time, it may be a microbial carbon source associated with nitrogen turnover (Seeley et al. 2020). Additionally, changes in soil available nitrogen, microbial biomass carbon and nitrogen caused by MPs may affect the rate of organic carbon mineralization (Liang et al. 2020). However, there were still limited studies on the effect of MPs on C/N coupling processes, and further studies are needed to explore this topic and its mechanisms, especially C/N intertwining involved in the conversion of MPs to DOC.

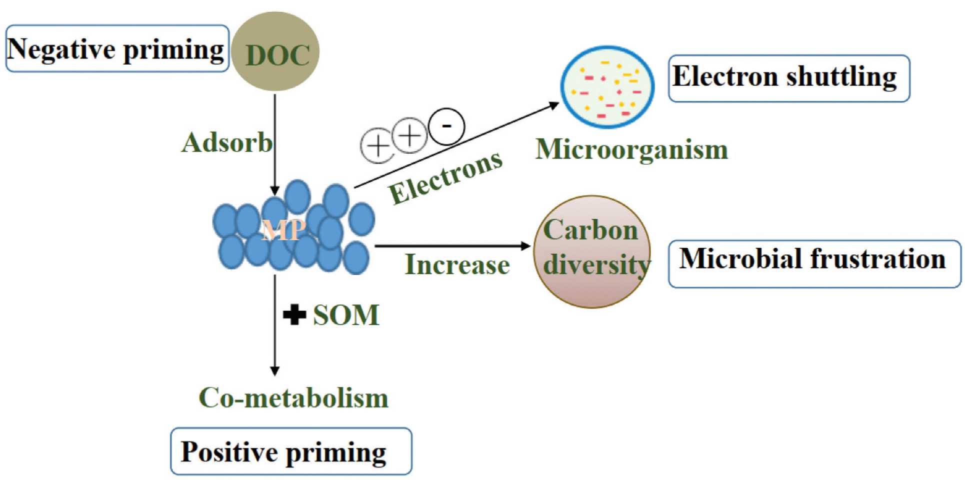

Figure 5. Testable mechanistic hypotheses of MP interaction with microbes in SOC cycling.

Conclusion, perspective, and challenges

MP pollution is widespread in terrestrial ecosystems, ranging from several particles/kg to thousands of particles/kg and may be affected by numerous factors. Through comprehensive analysis of the abundance, types, and shapes of MPs, it could be concluded that human industrial and agricultural activities are the most critical factors influencing the abundance and distribution of MPs in the terrestrial ecosystems. Once entering soil environments, MPs altered biogeochemical cycles, such as carbon and nitrogen cycles. These alterations can be direct via the properties of MPs (e.g., elemental composition, functional groups) and their metabolic intermediates. It can also indirectly change C and N turnover by influencing soil properties, especially aggregates, vegetation carbon and nitrogen pool input, microbial abundance and structure, related function genes, and enzyme activities. MP shape and type could affect these processes to a great extent, and in the current studies we summarized, it is found that biodegradable plastics have a more significant impact on carbon and nitrogen turnover in the terrestrial ecosystem.

Because of few relevant studies, the global effects of MPs on carbon and nitrogen turnover and their mechanisms are uncertain. It is highly expected to explore the carbon and nitrogen turnover process via microbes and their functional genes with isotope tracing and molecular biology technologies. Most current culture experiments only add specific MPs, which promotes microorganisms to use MPs as carbon sources and may deviate from the true situation. In addition, the experimental periods are often short in existing studies, whether in culture, pot, or field experiments. Future research should explore the long-term impact of MPs on carbon and nitrogen turnover and their related mechanism based on more actual situation. Furthermore, soil properties, plants, and microbes were sensitive to MP characters, such as its type, shape, size, nature of additives, and aging degrees. It is necessary to consider the influence and contribution rate of these complex parameters of MPs on the carbon and nitrogen turnover process.

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