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Review

Micro- and nanoplastics in soil: Linking sources to damage on soil ecosystem services in life cycle assessment

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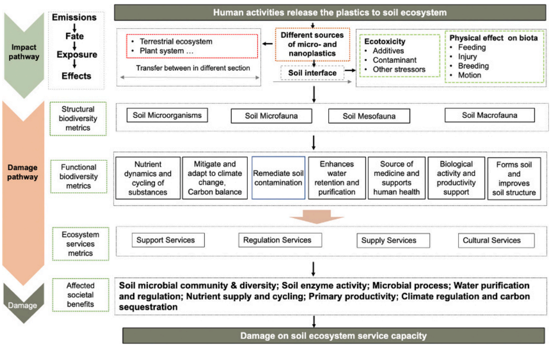
HIGHLIGHTS

- Micro- and nanoplastics (MNPs) pose risks to soil ecosystems and vital ecosystem services (ES).
- Sources, fate and effects of MNPs on soil ecosystems were demonstrated systematically.
- Life Cycle Assessment (LCA) needs to address MNPs-related damage to soil ES.
- Proposed conceptual framework links MNPs effects to species loss, functional diversity loss, and soil ES damage.

GRAPHICAL ABSTRACT



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ABSTRACT

Soil ecosystems are crucial for providing vital ecosystem services (ES), and are increasingly pressured by the intensification and expansion of human activities, leading to potentially harmful consequences for their related ES provision. Micro- and nanoplastics (MNPs), associated with releases from various human activities, have become prevalent in various soil ecosystems and pose a global threat. Life Cycle Assessment (LCA), a tool for evaluating environmental performance of product and technology life cycles, has yet to adequately include MNPs-related damage to soil ES, owing to factors like uncertainties in MNPs environmental fate and ecotoxicological effects, and characterizing related damage on soil species loss, functional diversity, and ES. This study aims to address this gap by providing as a first step an overview of the current understanding of MNPs in soil ecosystems and proposing a conceptual approach to link MNPs impacts to soil ES damage. We find that MNPs pervade soil ecosystems worldwide, introduced through various pathways, including wastewater discharge, urban runoff, atmospheric deposition, and degradation of larger plastic debris. MNPs can inflict a range of ecotoxicity effects on soil species, including physical harm, chemical toxicity, and pollutants bioaccumulation. Methods to translate these impacts into damage on ES are under development and typically focus on discrete, yet not fully integrated aspects along the impact-to-damage pathway. We propose a conceptual framework for linking different MNPs effects on soil organisms to damage on soil species loss, functional diversity loss and loss

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of ES, and elaborate on each link. Proposed underlying approaches include the Threshold Indicator Taxa Analysis (TITAN) for translating ecotoxicological effects associated with MNPs into quantitative measures of soil species diversity damage; trait-based approaches for linking soil species loss to functional diversity loss; and ecological networks and Bayesian Belief Networks for linking functional diversity loss to soil ES damage. With the proposed conceptual framework, our study constitutes a starting point for including the characterization of MNPs-related damage on soil ES in LCA.

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1. Introduction

Over the last few decades, an increasing amount of plastic has made its way into terrestrial environments. This plastic input undergoes a number of degradation mechanisms, including photo-decomposition and hydrolysis (Wong et al., 2020), resulting in the fragmentation into smaller pieces known as microplastics (Andrady, 2011; Auta et al., 2017). As this process continues, the size of the plastic particles can reach nanometer dimensions (Mitrano et al., 2021), in combination referred to as micro- and nanoplastics (MNPs). MNPs exhibit significant variation in form, chemical properties, texture, color, density and size (Rochman et al., 2016). These particles have been found to affect a diverse array of organisms form different habitats, trophic levels, sizes, feeding mechanisms, and behaviors (Kukkola et al., 2021). Consequently, MNPs have emerged as a significant pollutant.

MNPs pollution has been found to be ubiquitous, spanning from the equator to the poles (Lusher et al., 2015) from sea to land (Hu et al., 2022; Imhof et al., 2017). Recent evidence suggests that MNPs are present in various terrestrial ecosystems, including soil, and can enter through multiple pathways such as sewage sludge, irrigation, littering, atmospheric deposition, flooding, and plastic coverings (Xu et al., 2020), as shown in Fig. 1a. In Europe and North America, compost and sewage sludge are commonly used as fertilizers, and they are a significant source of soil plastic pollution in these regions. Additionally, China, Japan, and Korea account for 80 % of all plastic mulch, indicating that soil may be a large sink for MNPs (Geyer et al., 2017; Ng et al., 2018). Recent estimates suggest that that the annual input of MNPs from agricultural lands ranges from 63 to 430,000 tons in Europe and 440 to ~300,000 tons in North America (Guo et al., 2020). Furthermore, studies indicate that MNPs may be 4 to ~23 times more abundant on land than in the ocean (Nizzetto et al., 2016).

A high abundance of MNPs in soil has the potential to spread throughout various components of the soil ecosystem, including soil properties, fauna, microorganisms, and even functional traits within the plant community (Fig. 1b). This can result in potential threats to both the structure and function of the soil ecosystem. Due to their size similarity to algal or mineral particles, MNPs can easily be ingested by organisms at different trophic levels and accumulate in the food chain. Upon accumulation in organisms, MNPs may cause numerous negative effects, such as lethality, reduced feeding activity, inhibition of growth and development, endocrine disruption, energy metabolism disruption, oxidative stress, immune and neurotransmission dysfunction, and genotoxicity (Xu et al., 2020). Studies by He et al. (2021) and Liang et al. (2023) have highlighted the implications of this phenomenon, including its potential of MNPs to enter the food chain through trophic cascades.

Soil is essential for proving essential ES that support both human and ecosystem needs (Pereira et al., 2018). ES have direct and indirect contributions to human well-being but are under constant pressure from the intensification and expansion of human activities (Carpenter et al., 2009; Nelson et al., 2013). These services have social, ecological, economic, cultural and spiritual dimensions, and perform functions such as support, provisioning, regulation and cultural services (Fig. 1d). Soil

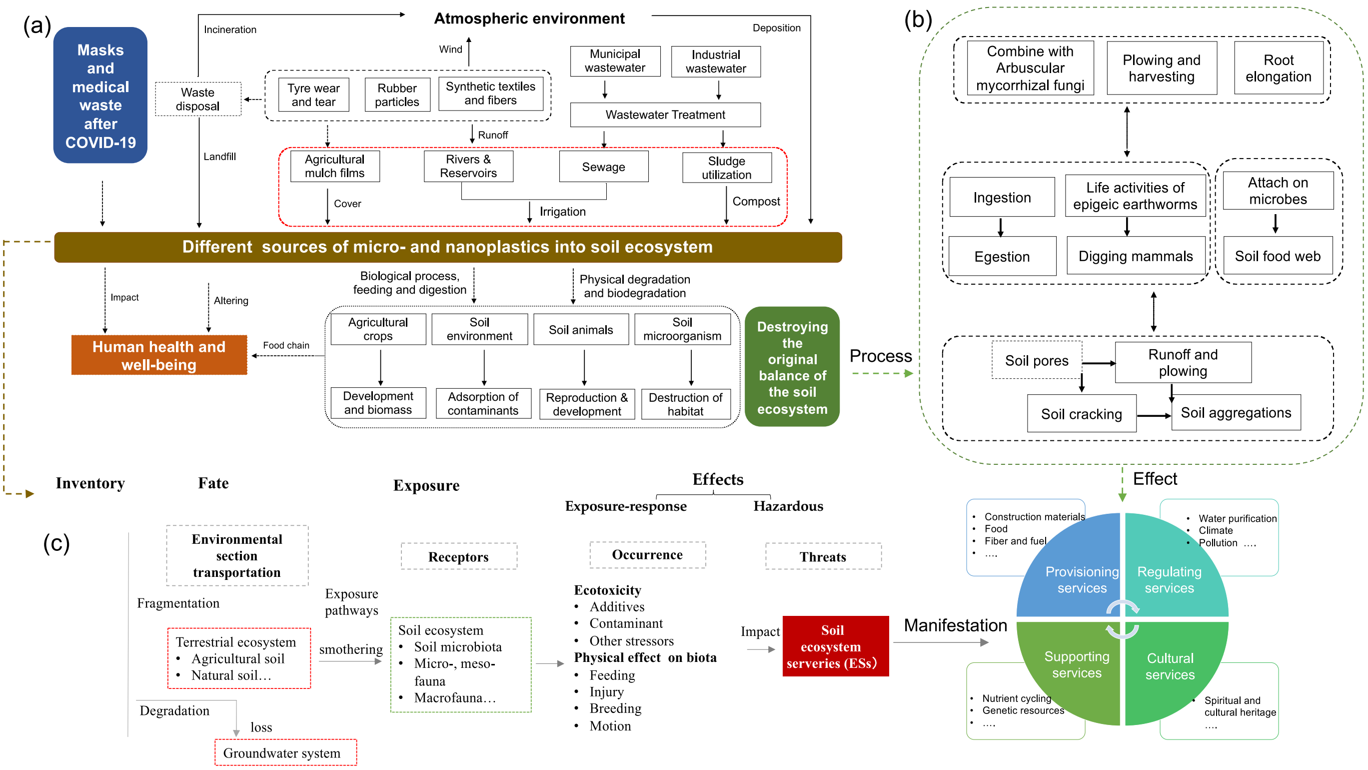

Fig. 1. Sources of micro- and nanoplastics (MNPs) and pathways into soil ecosystems (a), Environmental behavior of MNPs in soil (b); potential LCIA modeling framework for MNPs impacts in soil ecosystems (c); and functional attribute dimensions of soil ecosystems.

plays a critical role in biomass production, environmental purification, climate change mitigation, biodiversity maintenance, natural cultural heritage conservation, and landscape tourism resource development (Ananyeva et al., 2021; Comerford et al., 2013; Jónsson and Davíðsdóttir, 2016). Furthermore, 13 of the UN Sustainable Development Goals (SDGs) are directly or indirectly related to soils. Numerous studies have shown that soil organisms play an important role in the performance of ES (Lazarova et al., 2021). According to the Food and Agriculture Organization of the United Nations (FAO), soil biodiversity refers to the diversity of subsurface organisms (Costantini and Mocali, 2022; Orgiazzi, 2022), including both genes, species and their constituent communities, as well as the ecological complexes to which they contribute and to which they belong, including soil microhabitats and landscapes (Christmann, 2022).

LCA (Life Cycle Assessment) is a recognized quantitative decision support tool to identify options or solutions that have the lowest potential environmental impact, supporting the assessment and improvement of the environmental sustainability of products and technologies throughout their lifespan. LCA aims to quantify the pathway from stress to damage to ecosystems (Dieterle et al., 2022; Finnveden and Ekvall, 1998; Woods et al., 2018), including ecotoxicological impact pathways associated with chemical releases during the product life cycle (Fantke et al., 2018; Henderson et al., 2011; Oginah et al., 2023). A growing body of research highlights that MNPs is the form of plastic pollution with a high potential to cause negative environmental impact. Therefore, characterizing the effects that indicate the harmfulness of MNPs to soil ecosystems needs to be integrated as an important component of life cycle impact assessment (LCIA) (Fig. 1c). However, current LCIA methods do not yet include the damage to soil ecosystem functions, or damage to ES associated with MNPs-related effects (Pavan and Ometto, 2018).

Within LCA, recent efforts aimed at linking environmental impacts to the consequent damage on ecosystem services (Alejandre et al., 2019; Rugani et al., 2019). However, the integration of MNPs in this context is still missing. Notably, while ecotoxicity, a relevant component of MNPs, is acknowledged as an impact category within LCA, the connection between ecotoxicity and the consequential damage to ecosystem services remains insufficiently addressed (Oginah et al., 2023). This challenge arises from the complexity of quantifying and assessing the intricate interactions between stressors like MNPs and the varied ecosystems they influence. Consequently, there is a urgent need to refine existing methodologies and collect damage-related data for MNPs at ecosystem level, in conjunction with their related chemical ecotoxicity, and finally integrate that into the existing LCA framework. The preliminary methods designed to correlate environmental impacts with damage to ecosystem services have yet to integrate MNPs.

In summary, in MNPs' research, LCA is becoming more and more relevant. Although some methodologies can approximate damage to ecosystem services within LCA (Alejandre et al., 2019; Rugani et al., 2019), there is a plethora of review articles delving into MNPs in LCA (Gazal and Gheewala, 2020; Tan et al., 2023; Zhao and You, 2022). However, an evident gap exists in damage modeling, emphasizing the urgency of examining the implications of MNPs on terrestrial ecosystems and the associated detriment to soil ecosystem services. To quantify the damage caused by the effects of MNPs to the soil ES, it is necessary to define the basic pathway of from sources of MNPs to damage on species and functional diversity in soil ecosystems and link them to ES damage. To address this gap, the present study aims (a) to provide conceptual framework of linking MNPs sources to impacts and further to damage on ES, (b) to provide an overview of sources, fate, effects of MNPs on soil ecosystems, and (c) to discuss methods to link impacts to damage on soil species diversity, functional diversity and ES. This manuscript aims to address the gap by extending LCA to include MNPs and their damage on soil ecosystems and ecosystem services, partly building on existing reviews that so far focus only on the link of MNP emissions to effects on species, while not considering the link from effects to damage on related ecosystem services.

2. Methodology for identifying key literature

We employed a systematic approach for our review by using the Web of Science core collection database, focusing on articles in English published up until February 2023. Initially, we extracted a total of 1896 articles on soil MNPs. To further refine our search, we incorporated keywords such as “microplastics”, “life cycle assessment”, and “cascade model”, yielding 73 articles, 27 of which specifically dealt with soil ecosystems. In a subsequent refinement stage, we revisited the initial 1896 articles and added the keywords “species diversity”, “functional diversity”, and “ecosystem services”, which resulted in 36 additional relevant articles. After manual review and the exclusion of unrelated articles, we yielded a set of 57 papers that were particularly focused on LCA in relation to soil MNPs. These selected articles formed the foundation of our analysis.

3. Conceptual framework of linking micro- and nanoplastics sources to damage on soil ecosystem services

We propose a conceptual framework for linking MNPs impacts on soil organisms to related ES damage in LCA (Fig. 2). To quantify the damage on services provided by soil ecosystems, it is crucial to clarify the cascade relationship between the structure-function-services damage of MNPs on soil ecosystems, propose a feasible quantitative expression assessment method, and discuss the advantages, disadvantages, and possibility of data for each step from MNPs impacts to soil ES damage.

4. Sources, fate and effects of micro- and nanoplastics in soil ecosystems

4.1. Sources of micro- and nanoplastics in soil ecosystems

Multiple human activities introduce various types of MNPs into soil ecosystem as conducted by Zhao et al. (2022). These include the use of mulch in agriculture, utilization of sludge and solid waste composting in municipal sewage plants, sewage irrigation, plastic waste disposal, atmospheric deposition, and rainwater runoff as shown in Fig. 1(a).

Agricultural mulch and greenhouse cultivation enhances crop yield, they also increase soil MNPs level, which pose a serious threat to soil quality (Arsene and Fyama, 2021; Huang et al., 2020). Mulch films made mainly of polyethylene (PE) and polyvinyl chloride (PVC) and sometimes as thin as 8–50 μm, leave behind hard-to-recover residues, which degrade into MNPs due to factors like tillage and UV radiation (Yuan et al., 2022; Tian et al., 2022).

The use of sewage sludge in agriculture has introduced substantial MNPs amounts (Geyer et al., 2022; Rolsky et al., 2020), with the abundance rising with increased sludge application (Tian et al., 2022). Moreover, the abundance of MNPs in the products of fermentation or composting from different sources of solid waste (with different substrates) varies and can enter the soil system directly (Golwala et al., 2021). Another major route for plastics to enter the soil environment is through waste disposal (Horton and Dixon, 2018), which results from waste disposal activities associated with construction, agricultural and consumerism. Consequently, these activities cause the emission of MNPs into the soil. Kawecki et al. (2021) highlighted that waste disposal is the main pathway for plastics to enter the environment, with 40 times the mass flux of plastic entering the soil than water bodies.

Furthermore, MNPs can be transported to remote areas by atmospheric circulation and subsequently impacted by dry and wet atmospheric deposition (Szewc et al., 2021), which are then transported via wind to aquatic ecosystem or deposited on agricultural surfaces. MNPs can enter the soil through rainwater runoff (Sang et al., 2021; Wang et al., 2022) and atmospheric dust fall. Activities like sewage discharge,

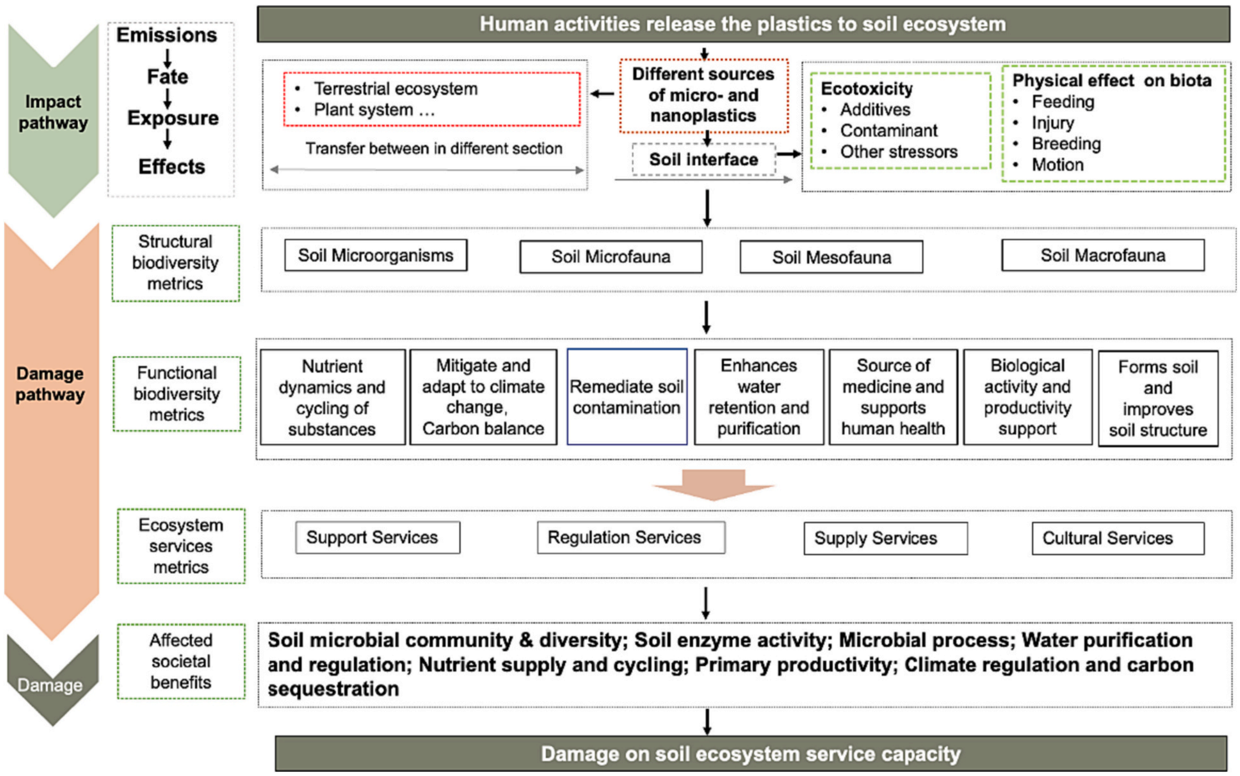

Fig. 2. Conceptual framework for linking impacts associated with micro- and nanoplastics on soil organisms to damage on structural biodiversity, functional biodiversity, and soil ecosystem services.
Adapted from Oginah et al. (2023).

irrigation, and agricultural mechanization further enhance MNPs' introduction into soils (Choi et al., 2021; Katsumi et al., 2021; Yi et al., 2021). It should be emphasized that the COVID-19 pandemic has generated a significant amount of masks and medical waste globally, constituting another important source of soil MNPs that cannot be neglected (Torres-Agullo et al., 2021). In essence, both human-made and natural processes contribute to the diverse sources of MNPs in soil, ultimately affecting the ecosystem's functionality.

4.2. Environmental fate and exposure processes of micro- and nanoplastics in soil

Soil is a crucial sink MNPs, influenced by the accumulation, migration, and transformation. These process within depicted in Fig. 3, determine how MNPs get retained in soil, biota, and ultimately move up the food chain, presenting potential human health risk to. Alternatively, MNPs may disperse into the atmosphere and water bodies.

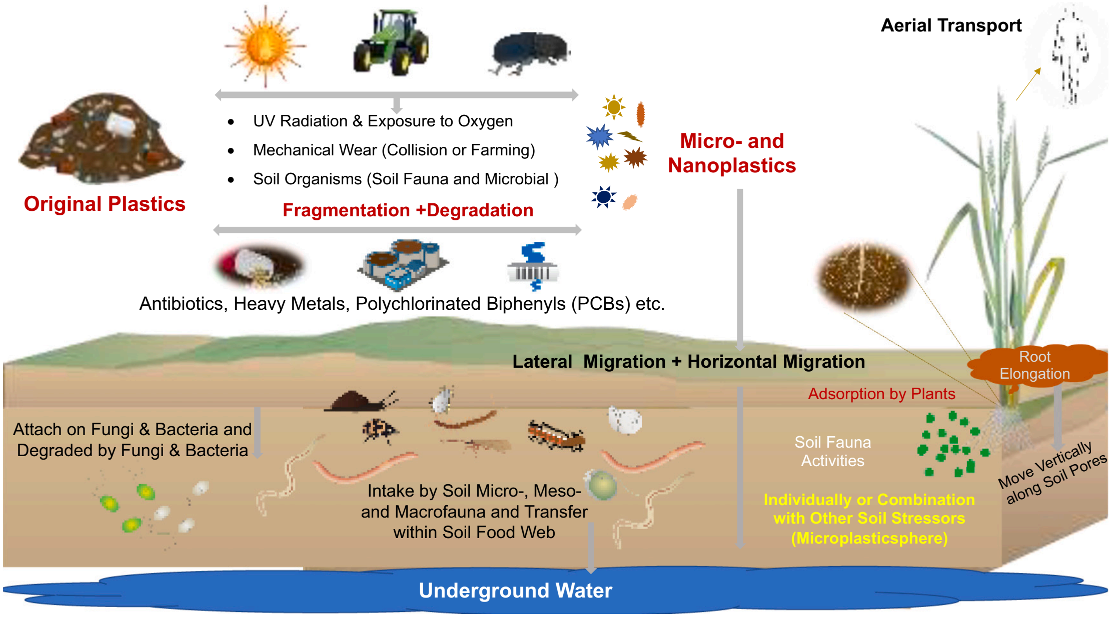

Fig. 3. Main environmental fate processes of micro- and nanoplastics in soil.

4.2.1. *Adsorption and desorption*

MNPs including Polystyrene (PS), Polypropylene (PP), Polyethylene (PE), effectively adsorb contaminants like antibiotics, heavy metals, polychlorinated biphenyls (PCBs), polycyclic aromatic hydrocarbons (PAHs), and organochlorine pesticides (i.e., Dichloro-diphenyl-trichloroethane, DDT; Hexachlorocyclohexane, HCH) from their ambient environment (Bank et al., 2020; Horton et al., 2017) from the surrounding environments due to various mechanisms like hydrophobic interactions, electrostatic interactions, pore filling, van der Waals forces, hydrogen bonding and π-π interactions (Horton et al., 2017). Several factors, including plastics properties, pollutant characteristics and environmental conditions (Bhagat et al., 2021; Khalid et al., 2021), influence this adsorption. While sorption behaviors of non-degradable MNPs are better understood, studies have recently suggested that degradable plastics might exhibit greater affinity to contaminants (Fan et al., 2021).

4.2.2. *Transformation*

MNPs undergo transformations via fragmentation and degradation, primarily through physical, chemical, and biological processes means, as illustrated in Fig. 3. Ultraviolet (UV) induced chemical degradation is the dominant initial transformation at the soil surface, resulting in various structural changes and producing smaller fragments and NPs (Jin et al., 2022; Tian et al., 2022). UV exposure combined with irradiation forces boosts MNP fragmentation, allowing for subsequent microbial degradation (Amobonye et al., 2021; Ranjan et al., 2021). Some insects, such as yellow mealworms and earthworms, also contribute to the degradation of MNPs (Jin et al., 2022; Yang et al., 2014).

4.2.3. *Migration and transport*

MNPs' distribution within soil is influenced by abiotic factors, such as wind effects, soil erosion, and surface runoff, and biotic factors including plants, soil fauna and microbial activity (Xi et al., 2022; Yang et al., 2022). Soil water dynamics and plant-root activities affect vertical MNPs migration (Rillig et al., 2017a). Earthworms activities influence MNP movement, with smaller particles migrating deeper (Lwanga et al., 2017; Rillig et al., 2017b). Plastic particle type, size and density also influence the vertical movement of MNPs in soil. Moreover, soil microbes alter MNPs migration patterns by modifying their properties (particle size, density, and surface properties, etc.) and structure (He et al., 2020; He et al., 2022). This migration of MNPs presents potential risks of contamination to humans and ecosystem, with certain organisms in soil food chain influencing MNP movement (Zhu et al., 2018).

4.3. *Negative effects of micro- and nanoplastics on soil organisms*

Soil organisms, including microorganisms and soil animals, are vital components of the soil ecosystem with diverse roles (Brussaard, 1997; Coleman et al., 2012; Wurst et al., 2012). MNPs have been found to negatively affect soil organisms through toxicity, physical damage, biological disruption, and soil properties alterations. MNPs not only release toxic substances harmful to microorganisms and worms but also affect their growth, reproduction, and overall health. Changes induced by MNPs in soil environment further affect nutrient cycling, plant growth, and overall soil health, as illustrated in Fig. 4 (Liu et al., 2023).

4.3.1. *Physical and chemical effects*

MNPs present various physical challenges to soil organisms, including ingestion by soil invertebrates, leading to internal blockages and organ damage (Cheng et al., 2021; Dong et al., 2021). They modify soil structure and nutrient availability, and reduce oxygen and water availability, disrupt microbial activity and nutrient cycling (Dong et al., 2021). Chemical effects arise from MNPs' additives that might leach, presenting environmental hazards (Gudeta et al., 2023; Khalid et al., 2021), and their ability to accumulate pollutants like heavy metals and organic chemicals.

NPs, with their increased reactivity and mobility, pose higher potential toxicity than MPs. They can influence soil structure and microbial activity (Kim et al., 2023; Vaccari et al., 2022) and act as carriers of diseases and invasive species. MNPs provide a substrate for microorganisms carrying plant pathogens, enabling the spread of plant diseases (Gkoutselis et al., 2021). They can also transport invasive species, like

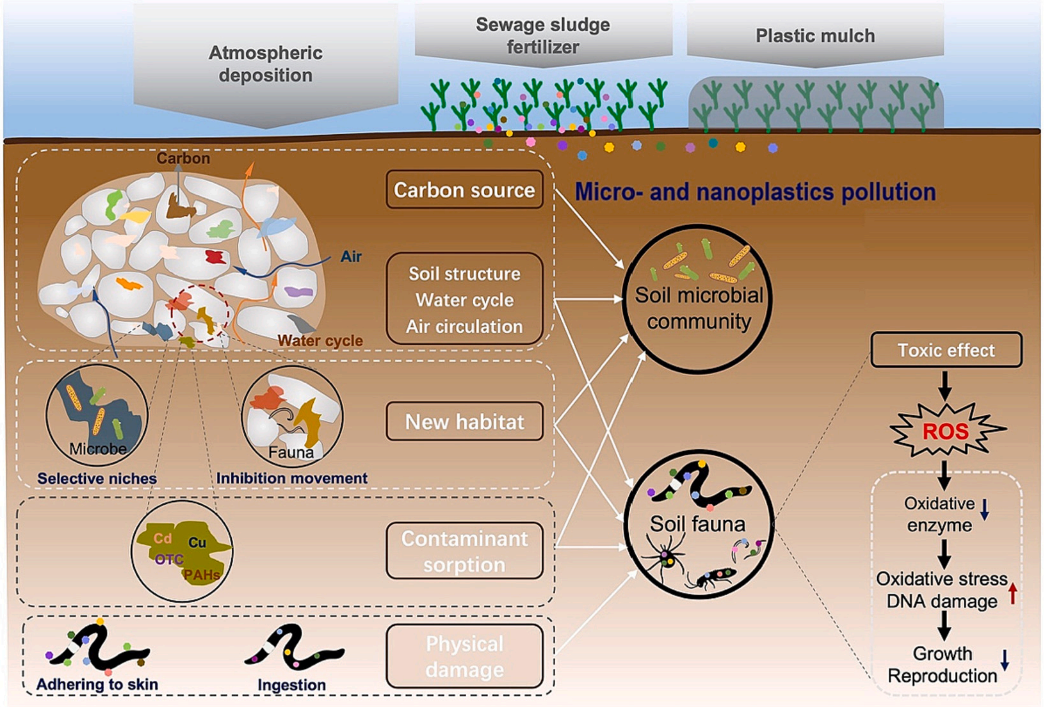

Fig. 4. Conceptual illustration depicting the potential effects of soil micro- and nanoplastics pollution on soil organisms (microbiota and fauna) from Liu et al. (2023).

insect eggs or seeds, over long distances, leading to the establishment of new populations in previously unaffected areas. Summing up, MNPs present varied threats to soil health, including physical, chemical, and nano-level impacts, coupled with disease spread and invasive species. Their influence on ecosystems is a rising concern, warranting further research.

4.3.2. Ecotoxicity effects

MNPs harm a range of soil fauna, including earthworms, nematodes, and mites (Chae and An, 2018; Huerta Lwanga et al., 2017). Soil fauna can ingest MNPs, leading to toxicity effects. MNPs may accumulate in food chains, inducing toxic impacts on organisms across various trophic levels (Rillig, 2012). Most research has concentrated on earthworms, revealing decreased survival and organic matter processing abilities (Yao et al., 2020; Zeb et al., 2020). Earthworms exposed to MNPs exhibit reduced growth, weight, and increased mortality (Lwanga et al., 2016; Boots, 2022). Large PE MPs inflict both pathological and immune damage on these earthworms (Rodriguez-Seijo et al., 2017). Smaller MNP degradation products can be ingested more easily by fauna, affecting their ecological functions (Ding et al., 2022; Wang et al., 2022). When combined with other pollutants, MNPs can intensify toxicity and shift soil microbe communities (Mao et al., 2022), though some findings show no marked combined impacts (Gaylor et al., 2013). A holistic understanding of MNPs' effects on soil fauna is crucial, factoring in diverse environmental and biological components (Ding et al., 2022; Yao et al., 2020). Current studies, mostly laboratory-based, might not represent real-world scenarios (Wang et al., 2022). Future research should focus on the combined ecological impact of MNPs.

Soil microorganisms are essential in the transformation and cycling of soil nutrients (Machado et al., 2018). MNPs influence enzyme activity, microbial biomass, and community diversity. The duration of plastics in the soil alters microbial community patterns (Fan et al., 2022; Zang et al., 2020). Specific MNP types can modify bacterial communities and soil properties, impacting essential functions like nitrogen and carbon cycling (Li et al., 2022). MNPs can favor certain microbes over others, changing microbial dynamics and critical ecological processes (Gao et al., 2021; Tang et al., 2023; Xie et al., 2021). These plastics can also intensify soil CO_2 emissions and modify bacterial community structures, but their effect on eukaryotic communities is less pronounced (Gao et al., 2021; Li et al., 2023). They influence denitrification processes and can boost certain fungi, which affects phosphorus cycling (Chen et al., 2020; Dong et al., 2021).

5. Methods to link micro- and nanoplastics impacts to damage on species diversity, functional diversity, and soil ecosystem services

To evaluate the impact of MNPs on soil ecosystems within the LCA framework, it is necessary to establish a linkage between the effects of MNPs and the resulting damage on species diversity, functional diversity, and soil ES. The adverse consequences of MNPs on soil ecosystems, when overlooked, can cause a ripple effect. Such cascading effects have the potential to disturb not only the biophysical elements but also influence socio-economic components, considering how deeply human communities are intertwined with these ecosystems. The urgency to understand these connections spurred the advent of the cascade modeling concept (Brink et al., 2016; Haines-Young and Potschin, 2010; Liu et al., 2020; Rugani et al., 2019). Originally, the cascade model was conceptualized to elucidate the connections between ecological structures, functional processes, and the ensuing benefits and values for humans (Haines-Young and Potschin, 2010; Maes et al., 2012). It has since evolved to provide a spatially explicit quantitative assessment of ecosystems, including the services and benefits they offer (Costanza et al., 2017; Spangenberg et al., 2014). Furthermore, researchers have refined and expanded the model for better application to socio-economic processes that result in changes to ecosystem structures, or for integration into broader causal frameworks like the Driving-Pressure-State-Impact-Response (DPSIR) framework (Bakshi et al., 2015; Burkhard et al., 2014; Ramos-Quintana et al., 2018). The DPSIR-framework analyses the causal links between human and environmental processes, encapsulating Driving force, Pressure, State, Impact, and Response (Miranda et al., 2020; Ta and Babel, 2023). For soil MNPs, the driving force encompasses increased global plastic usage and inadequate waste handling. This leads to the pressure of plastic accumulation in terrestrial areas. As plastics break down, they create a state where soils are saturated with MNPs, which both interact with and modify soil properties. This results in impacts like altered microbial activity, soil health decline, and MNPs acting as pollutant carriers, even infiltrating food chains through organisms like earthworms. Addressing these effects requires responses like better waste management, anti-single-use plastic policies, research on MNPs degradation, and public awareness. Noteworthy, while the framework does not specifically target “damage”, its “impact” pathway approach relates to various environmental consequences.

The evidence on the presence of MNPs in various terrestrial habitats and their potential toxicity and other effects has accentuated the need to integrate them into existing ecological models. Without a robust representation of MNPs in these models, we risk underestimating their potential impacts on soil biodiversity and the cascading effects on ecosystem services. Emerging literature accentuates the demand for a more comprehensive, dynamic, non-linear model to decode the intricate interplay between ES and human well-being (Costanza et al., 2017; Othoniel et al., 2016; Othoniel et al., 2019; Weidema et al., 2018). Such a paradigm ought to excel at distinguishing between services and benefits. It should valorize the multifaceted functions of ecosystems while deciphering the entangled matrix of ecosystem functions and their relationships to human well-being (Costanza et al., 2017). This enhanced cascade model shares numerous similarities with the causal model employed in LCA and is proposed to link LCIA impact pathways to damage modeling for assessing ES (Brink et al., 2016; Liu et al., 2020; Rugani et al., 2019). Ideally, such framework for linking impact pathways to damage on ES encompasses the full spectrum of impact category indicators used in LCA, their target beneficiaries, their interconnectedness at the conservation area level, and their spatial and temporal variability. While the existing cascade model already links several impact categories to ecosystem services in LCA, impacts from MNP emissions to soil are currently not considered. In the following sections, we will explore the requirements and potential approaches to connect MNP-induced effects to soil ecosystem service degradation within the LCA framework.

5.1. Linking soil micro- and nanoplastics related effects to damage on species diversity

A holistic assessment of MNPs-related damage on species diversity necessitates leveraging innovative, robust, and methodologically rigorous techniques. The TITAN (Threshold Indicator Taxa ANalysis) is one such promising approach tailored to quantify the effects of environmental stressors, including MNPs on soil ES diversity (King and Baker, 2014). Fundamentally, TITAN is anchored on identifying and harnessing the potential of indicator taxa — organisms that are inherently sensitive to specific environmental perturbations. The abundance of these taxa can serve as an effective proxy for gauging overall species diversity. Implementing TITAN offers a quantifiable metric of the damage to soil ES diversity caused by the MNPs. The TITAN method is suitable for translating predicted effects, such as physical and ecotoxicological effects of MNPs, into quantitative measures of damage to species diversity (Oginah et al., 2023). TITAN is a statistical approach that identifies a threshold level of stress at which there is a significant decrease in the abundance of sensitive indicator taxa, which are selected based on their known sensitivity to the stressor in question. The difference in the abundance of indicator taxa above and below the threshold level is used as a measure of the impact of the stressor on species diversity.

Beyond TITAN, a range of analytical techniques can be used to link MNPs' organism effects to damage on species loss in soil ecosystems. Quantile Regression can be an effective tool for understanding the relationship between MNPs effects and species loss (Cade and Noon, 2003; Chen et al., 2021). It captures the entire distribution of responses, allowing for a more comprehensive understanding of the potential impact on species diversity. Species Sensitivity Distributions (SSD) is another statistical method that could be used to understand the relationship between MNPs effects and species loss (Proctor, 2019; Song et al., 2022; Sørensen et al., 2020). SSDs estimate the variation in sensitivity to a particular stressor (e.g., MNPs) across a range of species, thereby being able to capture different effect types. The output can provide information on the proportion of species likely to be affected at different levels of exposure to MNPs (Mehinto et al., 2022; Kim et al., 2023). Dynamic Energy Budget (DEB) models can simulate the uptake, internal distribution, and effects of MNPs on the physiology of individual organisms, thus linking toxicological effects to population-level impacts (Catarino et al., 2022; Kashkooli et al., 2020). This can then be extrapolated to potential species loss. Finally, another potential approach is DNA metabarcoding to quantify changes in soil microbial community diversity in response to MNPs (Nelms et al., 2019; Santaella and Plancot, 2020). This approach involves analyzing the DNA of soil microorganisms to identify the different species present and can provide information about the changes in microbial community structure and diversity caused by the MNPs.

5.2. Linking species loss to damage on soil functional diversity

Assessing the damage to functional diversity caused by MNPs impacts on soil ecosystems can be done by using the trait-based approach (Chelinho et al., 2014; Oginah et al., 2023). This approach focuses on the traits of the species present in the ecosystem and their contributions to ecosystem functioning (Mason and De Bello, 2013). For instance, consider nitrogen fixation, a pivotal functional trait executed by specific species in the soil ecosystem. If MNPs negatively influence the abundance or activity of nitrogen-fixing organisms, the implications span various dimensions. This can result in diminished soil fertility, hampering plant growth, and eventually affecting ecosystem services like crop yield. Within LCA, such reductions in ecosystem services would equate to an enlarged environmental footprint for crop production, given the need for supplementary synthetic fertilizers.

Moreover, organisms such as earthworms, instrumental in organic matter decomposition and soil aeration, can serve as another benchmark. Their traits, like burrowing behavior, influence water infiltration and soil structure. A MNPs-induced decline in earthworm populations or alterations in their behavior could hence disturb water regulation functions and the soil's capacity to nurture plant life. In LCA terms, a decline in earthworm activity due to MNP emissions will lead to damage on ecosystem services, such as water regulation in soil.

The initial step in this approach is to pinpoint the functional traits of species crucial for the ES provided by the soil ecosystem, such as the ability of a species to fix nitrogen or decompose organic matter. Subsequently, the trait-based approach assesses the prospective loss of functional diversity attributable to MNPs' varied impacts on soil species. This is achieved by calculating the functional richness and evenness of the species within the ecosystem. Functional richness refers to the number of different functional traits present in the ecosystem, while functional evenness refers to the evenness of the distribution of these traits among the species (Mason and De Bello, 2013; Villéger et al., 2008). A decrease in either functional richness or functional evenness can indicate a loss of functional diversity.

To quantify the damage to functional diversity, the trait-based approach can be combined with a weighting method that assigns a value to each functional trait based on its importance for the provision of ES (de Souza et al., 2013). This can allow for a more accurate assessment of the various types MNPs effects on the functions provided by the soil ecosystem. To quantify the damage to functional diversity resulting from species diversity loss, one approach is to simulate the removal of species from the ecosystem and assess the resulting change in functional diversity (Echeverri et al., 2020). This can be done using mathematical models or experimental manipulations in the field or laboratory experiments. Another alternative is to scrutinize how species diversity shifts relevant ecosystem functions, for instance, nutrient cycling or soil structuring, followed by quantifying the damage to functional diversity (Brussaard, 1997; Trivedi et al., 2012). This can be done by measuring changes in functional diversity metrics following experimental manipulations or modeling the impact of species loss on ecosystem functions (Lazarova et al., 2021).

Incorporating the trait-based approach into LCA's damage assessment for MNPs is possible by leveraging midpoint or endpoint indicators (Antón et al., 2016; Sala and Goralczyk, 2013). Blending trait-based evaluation with Species Sensitivity Distributions (SSDs) provides a method to predict species loss risk from MNPs. By using SSDs in conjunction with trait-based studies, we can identify species with critical functional traits that are at the highest risk. Integrating this information into an LCA can help shed light on potential long-term impacts, specifically in terms of functional loss within the soil ecosystem.

5.3. Linking functional diversity loss to damage on soil ecosystem services

Understanding the potential damage of MNPs on soil ES requires a bridge between the loss of functional diversity and the consequential damages on soil ES. Incorporating ES assessments into LCA brings about a comprehensive perspective on this relationship (Sun et al., 2021; Vaccari et al., 2022). By quantifying the provision of soil ES, such as nutrient cycling, carbon sequestration, and water regulation, studies can determine how changes in soil biodiversity and function may affect soil ES. Such studies could help identify, which ES are most vulnerable to the impacts of MNPs, and which management strategies may be most effective in minimizing related ED damage. ES assessments can therefore help link the impacts of MNPs on soil ecosystem species and functional diversity to damage on soil ES (Adhikari and Hartemink, 2016).

To integrate soil ES assessments into LCA, it is necessary to identify the links between soil ecosystem species and functional diversity on the one hand and the provision of ES on the other hand. A practical illustration lies in the role of diverse soil organisms for nutrient cycling. These organisms, from the smallest bacteria to larger fauna like earthworms, influence the breakdown and cycling of organic and inorganic materials. Disruptions caused by MNPs can affect these processes. If beneficial microbes responsible for nitrogen fixation are reduced due to MNPs, the downstream impact might be a decline in soil fertility, necessitating increased fertilizer use with all its associated negative ecosystem service implications.

To translate functional loss to ES damage, a variety of approaches can be used as a starting point. (1) Functional trait-based approach focuses on linking functional traits of species with ES (Waldén et al., 2023; Weiss and Ray, 2019). In this approach, key functional traits associated with specific ES are identified to quantify the impact of functional loss on those services. For instance, some fungi facilitate plant root absorption through mycorrhizal associations. The degradation of these fungi due to MNPs can result in plants having diminished access to essential nutrients. (2) Ecological network-based approaches focus on the relationships between species and their interactions within an ecosystem. By understanding the interconnectedness of species within ecosystems, we can visualize the cascading consequences of functional diversity loss (Felipe-Lucia et al., 2021; Windsor et al., 2021). Consider soil mites, which feed on detritus, aiding decomposition. A decline in these mites might affect larger predator populations and the overall rate of decomposition, thereby influencing soil organic matter levels and carbon storage capacities. (3) Bayesian Belief Networks (BBNs) are graphical models that can be used to represent complex causal relationships between variables. BBNs can be applied to link functional loss to ES and estimate the probability of damage to specific services (Ouyang et al., 2019; Pham et al., 2021). For instance, BBNs could model how a decline in soil fauna responsible for pore creation might affect soil water retention, aeration, and, in turn, plant health and productivity.

6. Challenges for practical implementation

Assessing MNPs' damage on soil ES demands an integration of laboratory studies with field data at various levels. Typically, ecotoxicology employs field-derived ecological concepts and laboratory toxicity assessments. A synthesis of these methods offers a nuanced understanding of chemical-related impacts of MNPs, factoring in their degradation, soil interactions, and potential to absorb other pollutants (Hu et al., 2022; Imhof et al., 2017). MNPs' diverse properties, such as size and polymer type, further influence varied ecological outcomes. It is essential to analyze both individual species reactions and broader ecological consequences to enable linking MNP effects to soil ES damage. Effective assessment necessitates aligning predicted damages with field observations to validate LCA models (Fantke et al., 2018; Henderson et al., 2011; Oginah et al., 2023). For instance, while lab results might indicate MNPs stunting soil bacteria growth, field studies could show faster degradation, reducing impact (Fan et al., 2022; Li et al., 2022). MNPs can alter soil attributes like water retention and porosity and hint at continuous ecological threats. The study of MNPs' bioavailability and soil distribution is vital. They can serve as pollutant carriers, and combined with other contaminants, shape soil biology (He et al., 2021; Liang et al., 2023). Factors like soil type and climate further determine MNPs risks across different terrains. Comprehensive insights into MNPs effects on soil demand a strategic fusion of ecological theory, fieldwork, and lab research, which all needs to be aligned with the boundary conditions of LCA, thereby constituting a considerable practical challenge.

Effective ES management hinges on insights from biomonitoring and rigorous analysis. Monitoring MNPs in soil and their implications for ES degradation is hence vital. MNPs differ in type, size, and source, making them distinct from common pollutants (Liu et al., 2023). Their origin, be it agricultural runoff or urban wastewater, impacts their degradation and interaction with soils. Their degradation might release other pollutants, altering soil functions, highlighting the complexity of MNPs pollution. This constitutes a practical challenge, since it requires considering interactions across different impact categories in LCA (e.g. ecotoxicity and MNP impacts). In addition to stressor interactions, different stressors exhibit spatial and temporal variations; hence, an integrated approach becomes indispensable for a complete understanding of their collective influence. For example, research conducted in the Mediterranean highlighted that areas exposed to both pesticides and MNPs experienced a significant drop in soil fertility, suggesting a combined stressor effect assessment (Llorca et al., 2020).

The environmental science realm is rife with challenges, particularly in ES monitoring. These range from combining diverse ES monitoring data to incorporating various socio-cultural values and knowledge (Liu et al., 2020; Rugani et al., 2019). For MNPs, unique challenges arise due to their varied properties. These characteristics often call for specialized monitoring and analytical tools. Overcoming these challenges requires improving data collection methods, refining analytical frameworks, and crafting tools that merge ES monitoring data with evolving stressor trends. The ultimate goal is to develop an LCA framework that fully addresses direct and indirect impacts of soil MNPs on ES. Therefore, our task is to continuously optimize the model to ultimately achieve the desired value between the theoretical damage prediction and the actual damage.

7. Conclusion and future research

In the present study, we provide an overview of sources, fate and effects of MNPs on soil ecosystems, and propose different approaches for linking these effects to damage on soil species loss, functional diversity loss and ultimately to damage on soil ES for inclusion into the LCA framework. Current methods do not include MNPs and their related effects on soil ecosystem quality, such as damage on species diversity, functional diversity, and soil ES. Therefore, it is necessary to integrate new approaches within this framework to encompass MNPs-related damages. To link the effects of MNPs to soil species loss, several methods have been introduced. Threshold Indicator Taxa Analysis (TITAN), for example, identifies shifts in species distribution across environmental gradients, offering a comprehensive view of potential MNPs impacts. Other techniques such as Species Sensitivity Distributions (SSD), Dynamic Energy Budget (DEB) models, and DNA metabarcoding provide different yet effective ways of understanding the relationship between MNPs effects and soil species loss. To assess the damage on soil functional diversity, a trait-based approach has been suggested. This focuses on the traits of the species present in the ecosystem and their contributions to ecosystem functioning, giving insights into potential loss of functional diversity due to MNPs. Finally, to link functional loss to damage on soil ES, a variety of approaches can be applied, including functional trait-based approaches, ecological network-based approaches, and Bayesian Belief Networks (BBNs). These techniques allow to represent complex causal relationships and estimate the probability of damage on specific soil ES. In summary, these approaches help linking MNP effects on soil species to related loss of soil ES for integration into the LCA framework. However, more research is needed to refine these methods and consistently combine them for use in LCA damage modeling.

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CRediT authorship contribution statement

Conceptualization, T.L., P.F. and H.L.; Data curation, T.L.; Funding acquisition, P.F., X.C.; Investigation, Z.X., H.L., and X.C.; Methodology, T.L., L.C., Z.X. Software, T.L.; Supervision, P.F. and X.C.; Visualization, T.L, L.C.; Writing - original draft, T.L.; Writing - review & editing, T.L., L. C., H.L., P.F., Z.X., X.C. All authors have read and agreed to the published version of the manuscript.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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