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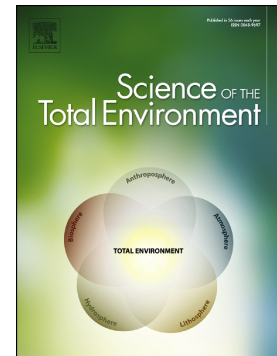
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The Plasticene era: current uncertainties in estimates of the hazards posed by tiny plastic particles on soils and terrestrial invertebrates

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Abstract

Plastics are ubiquitous in our daily life. Large quantities of plastics leak in the environment where they weather and fragment into micro- and nanoparticles. This potentially releases additives, but rarely leads to a complete mineralization, thus constitutes an environmental hazard. Plastic pollution in agricultural soils currently represents a major challenge: quantitative data of nanoplastics in soils as well as their effects on biodiversity and ecosystem functions need more attention. Plastic accumulation interferes with soil functions, including water dynamics, aeration, microbial activities, and nutrient cycling processes, thus impairing agricultural crop yield. Plastic debris directly affects living organisms but also acts as contaminant vectors in the soils, increasing the effects and the threats on biodiversity. Finally, the effects of plastics on terrestrial invertebrates, representing major taxa in abundance and diversity in the soil compartment, need urgently more investigation from the infra-individual to the ecosystem scales.

Keywords. Microplastics; nanoplastics; environmental pollution; trojan effect; toxicity

1. Introduction

Plastics are omnipresent in our daily life as wrapping, plastic-made items (Rodrigues et al., 2019; Li et al. 2023), or constituents of cosmetics and personal care products (Sun et al., 2020). Plastics can be produced with many different properties which, in combination with low-cost in production, make them ideal for almost any shape with the desired flexibility, durability and stability (Birley, 2012). The world's plastic dependence is reflected by the wide array of short time use plastic-made - plastic-containing - items including textiles, furniture, packaging, or healthcare products (Geyer, 2020). By adopting plastics into every aspect of our lives, plastic

production has grown exponentially, from almost no production in the 50s to about 460 million tonnes a year in 2019 (Jambeck et al., 2015; Geyer et al. 2017; Plastics Europe, 2018; OECD, 2022). The recent COVID19 pandemic has further boosted plastic production owing to the strong demand for personal protective equipment (gloves, gowns, hand sanitiser bottles, masks) (WHO, 2020). In sum, in a few decades plastic use has become ubiquitous and now represents one of the most significant environmental issues, all of this placing the world in a Plasticene era.

Plastic recycling and waste management remain inadequate, inefficient, or even non-existent in many regions of the world (OECD, 2022). Consequently, massive amounts of plastic objects and debris are improperly stored and progressively discharged into the environment. Shockingly, few actions aim at reducing the 22-39 million metric tons (Mt) of meso-, macro- and microplastics leaking to the environment every year (Lau et al., 2020; OECD, 2022). Between 1950 and 2015, it has been estimated that 4900 Mt of the total world's plastic production ended up in landfills and natural environments (Geyer et al., 2017). Moreover, nanoplastics are difficult to retain in the waste-water treatment process (Murphy et al., 2016; Ali et al., 2021; Šaravanja et al., 2022). As small sized plastics debris from cosmetics, personal care products, fibers and debris from polymer textiles and fiber-reinforced plastics are hardly detected in the environment, our current calculations of environmental plastic pollution are likely underestimated.

Plastic leakage in the environment has long-lasting economic, health and ecological consequences. Plastic debris can accumulate and persist in the environment for decades, or even centuries (Chamas et al., 2020). For example, Otake et al. (1995) reported that polystyrene and polyvinyl chloride were not degraded 32 years after they were buried into soil. These authors also found little degradation of a low density polyethylene bottle (Ohtake

et al., 1995). Using the specific surface degradation rate, plastic half-lives were estimated to range from 58 years (bottles) to 1200 years (pipes) (Chamas et al., 2020).

In the environment, plastic fragments of different polymers are found: high- and low-density polyethylene (HDPE, LDPE), polypropylene (PP), polyvinyl chloride (PVC), polyethylene terephthalate (PET), polyurethane (PUR), and polystyrene (PS). Plastic fragments also have different sizes (macroplastics (MAP), > 5 mm; microplastics (MP), 5mm - 1000 nm; and nanoplastics (NP), < 1000 nm) (Gigault et al., 2018) and shapes. Primary (*i.e.* produced for commercial or industrial purposes) and secondary MP and NP (*i.e.* produced from the degradation of larger plastic debris) accumulate in most environments (Andrady, 2011; Rillig and Lehmann, 2020; Allen et al., 2022a, Aliko et al. 2022) and are nowadays ubiquitous (Alimi et al., 2018; Patil et al., 2022; Allen et al., 2022b). While the presence of plastic wastes in the oceans is well known, it has been quantified more recently upstream in landfills (He et al., 2019), agricultural soils (Wahl et al., 2021), urban effluents (Ziajahromi et al., 2017) and rivers (Lechner et al., 2014; Dris et al., 2018). With regards to soils, however, this problem only recently reached the necessary attention (Rochman, 2018; Baho et al., 2021). This is surprising when considering that MP soil contamination can be 4-23 times higher than the yearly amounts of plastic wastes released in the oceans (Horton et al., 2017; de Souza Machado et al., 2018; FAO, 2021).

A growing body of literature reports the deleterious effects of environmental plastic accumulation on the life cycle of organisms and on numerous biogeochemical processes in the soil. Plastic accumulation interferes with soil aggregation, structure and bulk density, pore size and availability with cascading consequences on water dynamics, aeration, microbial community composition and activities. Moreover, plastic debris impact soil pH and conductivity, and therewith nutrient cycling processes, seed germination and plant growth, thus impairing agricultural crop yield (Boots et al., 2022; Rillig et al., 2021; Sajjad et al., 2022;

Maddela et al., 2023). The ubiquitous presence of plastic fragments in the environment also increases the risk of chronic or acute exposure of soil fauna, particularly earthworms and arthropods which represent the greatest diversity of terrestrial animals and provide many ecosystem services. By being present in soils, plastic fragments can be absorbed by plants, thus contaminating fruits and vegetables with uncertain consequences for animal consumers, including humans, and more broadly for ecosystems (Conti et al., 2020; He et al., 2021; Colzi et al., 2022; Dainelli et al., 2023).

To identify data gaps in scientific knowledge on the intensifying environmental impacts of plastic pollution, we first summarize the current information on the status of plastic pollution in agricultural soils, the concurrent threat to soil functionality, and the roles of plastic debris as vectors of other contaminants. We then evaluate the consequences for organisms and biodiversity, and discuss the main challenges that remain to be overcome in future studies. By realerting on the presence of MP and NP in soils, we evidence the crucial need for additional investigations on the effects of MP and NP on (a) soil water infiltration and retention capacity, (b) soil organic matter content and soil properties in general, and (c) the need for documenting the behavior of MP and NP in soils. Within the growing research concerning plastic-related environmental issues, the present perspective article highlights research gaps in our understanding of the effects of plastics on soil organisms. In particular, it is concluded that further investigations on the transfer of MP and NP in the soil food web, from soil organisms to other ecosystem compartments, and on effects of MP/NP at the different organizational scales (organism to community to ecosystem) are needed.

2. The fate of plastic pollution in agricultural soils and spotlights on research challenges

Functional soils deliver numerous ecosystem services. The production of more than 80% of the food consumed by humans, the regulation and supply of clean water as well as the

regulation of climate through carbon sequestration rely on soils. These services involve the activity of soil organisms (Barrios, 2007). Soils, including agricultural soils, where PE, PP and PVC debris are frequently found, risk becoming plastic waste sinks (Hurley & Nizzetto, 2018). In North America, 44 to 300 kt of microplastics per year are transferred to the soil (Nizzetto et al., 2016), with significant impacts on human health (Li et al., 2023). Soil plastic pollution can be so significant that FAO experts estimated that the quantities of plastic present in agricultural soils exceed those measured from aquatic and marine ecosystems (Nizzetto et al., 2016; Hurley & Nizzetto, 2018; FAO, 2021).

Plastic pollution of soils has a variety of sources: plastic soil covers and mulches, water pipes for irrigation or drainage, bale twine and wraps, containers, packaging and netting, polymers for seed coating, many of which often contain incorporated pesticides (Steinmetz et al., 2016; Horton et al., 2017); the application of composts from household waste are additional sources of plastic pollution in soils. As 99% of MP and NP remain in the sludges during water treatment processes (Magnusson & Norén, 2014), their subsequent use as fertilizers in agriculture, or during landscaping (Raju et al., 2018) represents an additional way for plastic debris to enter soils (Figure 1).

In soils, degradation of plastic debris occurs merely at the surface under UV light and temperature-enhanced oxidation (Andrady et al., 2022). This leads to chemical changes of plastic debris such as breaking or introduction of chemical changes increasing plastics' hydrophilicity and therewith their transport possibilities. In deeper soil layers, (anaerobic) degradation is, however, limited to either very little mechanical-chemical interactions, leached acidity or to limited biodegradation (bacteria, fungi, microfauna). Plastic degradation by bacterial communities (measured as plastic weight loss) depends on soil type and its conditions, and on the type of plastic debris (Huang et al., 2021). For instance, it is very slow

and inefficient for PVC, PP, more efficient for PU and HDPE products, and to some extent for LDPE and PS (Maddela et al., 2023). The activity of soil macrofauna adds to this plastic degradation with the help of their gut microbiome, by the action of chewing and shredding, or by interactions between plant and their microbiota (Pérez-Reverón et al., 2023 and references therein) (Figure 1). Finally, the soil itself can be an important driver of plastic fragmentation by acting as an 'environmental grinder': changes in soil volumes resulting from natural hydration and dehydration cycles could lead to a random fragmentation process (Berenstein et al., 2024).

In soils, the smallest particles (NP) can be transported by vertical processes: upwards by root actions and downwards with water infiltration to the underlying groundwater (Chia et al., 2021). Nanoplastics are regulated by the physico-chemical properties of soil and by their own characteristics (Pérez-Reverón et al., 2023). Factors controlling these fluxes include physicochemical soil properties, *e.g.* structure, porosity, organic matter content, pH *via* surface charges, infiltration capacity and water retention. The existing literature reports a high variability in the behavior and impacts of plastic debris in soils, most probably reflecting the diversity of MP and NP types, the heterogeneous characteristics of the studied soils, and the current challenges in the detection and quantification of these pollutants in complex environmental matrices, particularly for NP (Cai et al., 2021). Micro- and macro-fauna (in particular earthworms) may also translocate MP and NP via their activities (Heinze et al., 2021). Translocation of MP including adherent bacteria and metal pollutants by springtails has been evidenced, which in turn influenced soil bacteria community and function (Luo et al., 2023). Meanwhile, despite recent studies, we still have limited knowledge on the modalities of their transport, including transfer by soil fauna and burial by agricultural practices, and this requires more investigation (Huerta Lwanga et al., 2017; Maddela et al., 2023).

In soils, the characteristics of NP pose numerous research challenges: sampling, discrimination and identification of these particles embedded among other natural and/or anthropogenic carbonaceous particles. For these reasons, there is currently no reliable quantitative data on NP in soils. Estimates by Besseling et al. (2019) suggest concentrations of NP (< 100 nm) to be ~ 1,000 times higher than those measured for MP. In soil contaminated with plastics from a compost amendment, Wahl (2022) determined an average of 251 particles of MP kg⁻¹ of soil, but agricultural soil contamination by MP can reach values as high as 13,000 particles kg⁻¹ of dry soil (He et al., 2021). Conversely, we have little knowledge of NP concentrations in soils, and the collection of accurate quantitative information thus represents an emerging research field. Moreover, soil is a heterogeneous material whose specific characteristics are defined by its composition (clay, silt, loam), and by the quality and quantity of its organic matter (humus). Soil characteristics may also change with soil depth, and, on a very fine scale, horizontally with the presence or absence of organisms such as earthworms, plant roots, and microorganisms (Lavelle & Spain, 2002). This heterogeneity needs to be addressed in the research of MP and NP dynamics in soil.

In sum, there is an urgent need to gather knowledge of the quantities of plastic debris present in soils, and to rapidly develop reliable and reproducible quantification methods, in particular for NP. In the recent EU directive to protect soil (European Commission, 2023), reducing pollution is one of the targets which does include plastics. Improved knowledge of the impacts of MP and NP on the environment, including soils, is needed to support the "International Plastic Treaty", a resolution taken by the United National Environmental Assembly (UNEA). To date, work on the impact of plastic contamination has been limited to (1) the characterization of the distribution of different particle sizes, (2) the nature of associated polymers and their additives in natural environments, and (3) on the impact of MP and NP on living organisms. In addition, the monodisciplinary nature of most studies prevents us from obtaining a general, integrative and environmentally realistic vision of the

impregnation of plastics in the environment, their dynamics, and cascading impacts on environmental health. Here, we emphasize that the lack of data on the environmental factors governing aggregation and dynamics (degradation, flux, release) of MP and NP in soils is a major obstacle to accurate assessments of the impact of plastic debris (Figure 1). We also advocate for more projects gathering multidisciplinary teams of experts in soil and contaminant biogeochemistry, particle physico-chemistry, soil ecology, biological diversity and ecotoxicology. Such consortia could produce cutting-edge data on the life cycle of plastics and associated pollutants, their behavior and dispersion, as well as their impact on terrestrial living organisms.

3. The role of plastic debris as contaminant vectors in soils: where do we stand?

In the environment, plastic fragments can bind or attract other pollutants, leading to Trojan horse effects (Hu et al., 2022; Zhang & Xu, 2022). Due to their ultrahigh sorption capacities, MP and NP have strong potential for transporting other environmental pollutants: the sorption coefficient of polychlorinated biphenyls by microplastics could be up to 10^6 l kg^{-1} , and polyethylene film residues could concentrate more pesticides ($584 - 2284 \text{ } \mu\text{g pesticide g}^{-1} \text{ plastic}$) than soil ($13 - 32 \text{ } \mu\text{g pesticide g}^{-1} \text{ soil}$) (Ramos et al., 2015). It is also important to bear in mind that plastics are manufactured with different additives to reach the chosen physicochemical and visual characteristics and properties. These additives include plasticisers, UV stabilizers, anti-oxidants, flame retardants, and biocides, being made of phthalates, bisphenols, metals, metal oxide nanoparticles, all of them having the potential for being released into leachates (Hahladakis et al., 2018). One of the phthalic acid ester plasticisers, di (2-ethylhexyl) phthalate (DEHP) with known endocrine effects, is added to plastic used for agricultural mulch films to increase their elasticity and stability, but as it is not covalently bound, it leaches directly into the soil, water and air (He et al., 2014). Other phthalic acid ester

plasticisers from polyethylene cover used in agriculture, such as the dibutyl phthalate and its degradation product monobutyl phthalate, also migrate in the environment and affect the reproduction of earthworms (Berenstein et al., 2022). MP and NP can also be sources of microorganism transport, as those debris provide substrate for the development of bacterial communities, resulting in the formation of a plastisphere promoting the spread of pathogens and resistance genes (Wang et al., 2022a).

Adsorbed hydrophobic organic contaminants and metals or metalloids, along with the leachable plasticizers or additives, render microplastics a cocktail of hazardous chemicals for living organisms (Wang et al., 2020). Plastic additives such as phthalates and bisphenols are a significant source of endocrine disruption (ED) (Canesi & Fabbri, 2015; Gunaalan, et al. 2020). Although the toxicity and ED induced by these pollutants are known, MP and NP are not subject to environmental quality standards due to a lack of data on their effects on living organisms. The “International Plastic Treaty” by the United National Environmental Assembly (UNEA, 2022) decided to develop an international legally binding instrument on plastic pollution, addressing the full life cycle of plastic, and calls upon all member states to move forward with all necessary actions against plastic pollution. This includes, amongst others, to develop and implement national action plans, and to increase scientific knowledge and socioeconomic assessments related to plastic pollution (see Stöfen-O’Brien, 2022).

To date, we have little knowledge on the dispersion of plastics (MP, NP and their additives or co-contaminants) or impacts on water cycles, or soil functions. Although few studies deal with plastics in water cycle (Wan et al. 2019) or soil function (Qi et al. 2020), investigations on the effects of co-exposure of MP with plastic additives and their effects on wildlife, or the effects of cocktails of NP, plastic additives, and pesticides on living organisms are still urgently required. In particular, future investigations should consider the diversity of contaminating substances potentially associated with plastics, including the nature of the

additives and co-contaminants. Research priorities and experimental methods aiming at characterizing the effects of the plastisphere in soils were recently developed by Wang et al. (2022a). Such investigations would provide valuable information on the effects of the plastisphere on biogeochemical and ecological processes.

4. From assumptions to evidence: the need for collecting information on the effects of nanoplastics on soil invertebrates

Ingestion of plastic fragments by animals does not necessarily result in lethality; yet, it can have significant effects on life traits and cause cytotoxicity, necrosis, and even carcinogenic effects (Banerjee & Shelper, 2021). While the impact of microplastics has been demonstrated on the growth, metamorphosis, and fecundity of freshwater and marine invertebrates, the molecular mechanisms behind these effects are not well understood (Cole et al. 2015; Sussarellu et al., 2016; Leung & Chan, 2018; Lo & Chan, 2018; Murphy & Quinn, 2018; Ziajahromi et al., 2018).

Ingestion of plastic fragments can limit organisms' energy acquisition (false satiety or reduced nutrient absorption) or lead to changes in energy allocation. In particular, plastic ingestion can force organisms to increase their energy requirements to repair and maintain key biological processes at the expense of other important biological functions such as reproduction and growth. Several recent reviews summarized the impacts of plastics' ingestion on terrestrial and soil organisms (microbiota, macroinvertebrates, mice and plants, see Wu et al., 2021; Hodkovicova et al., 2022; Jiménez-Arroyo et al., 2023; Liu et al., 2023). Generally, most of the literature agrees that smaller particles have more harmful effects. MP and NP can alter molecular (DNA damage), physiological (ROS production, lipofuscin accumulation, immune priming) and cellular (neurological maldevelopment) processes; they

can also cause biological damages (apoptosis, histological damages, reproductive disorders, lifespan reduction, transgenerational effects) (Détrée & Gallardo-Escarate, 2018; Sharifinia et al., 2020). Finally, exposure to plastic fragments and their additives may also have unknown and long-term effects, with accumulation of damages across multiple generations. The literature reporting transgenerational effects of MP and NP ingestion in terrestrial organisms is still scarce in comparison with aquatic species (Junaid et al. 2023). There are however few studies conducted with model terrestrial organisms (nematodes, earthworms and flies) which have evidenced that plastic particles can accumulate over multiple generations (Liu et al., 2021; Sobhani et al., 2021; Tu et al., 2023). It is likely that long-term exposure increases sublethal toxicity, even at very low MP and NP concentrations, and future studies should thus explore the transgenerational effects of MP and NP exposure in terrestrial invertebrates.

MP and NP toxicity has been widely tested experimentally, but the actual ecotoxicological risk still lacks the necessary environmental realism in terms of the complexity of MP and NP sizes, shapes, materials and additives (Lambert et al., 2017; Boots, 2022; Figure 2). Importantly, as their physical and chemical properties vary, MP and NP cannot be regarded as one group for ecotoxicity testing. Similar to particulate matter, size may be a pivotal factor: the smaller the more dangerous (Huo et al., 2022). Moreover, fiber- and needle-like structures may be more harmful than spherical ones, as they more readily interact with and attach to biotic structures (Lambert et al., 2017 and citations therein). Thus, more detailed toxicological investigations are required to better take into account the physicochemical variability and environmental modifications due to weathering of MP and NP. Plastic debris and its co-contaminants, when ingested by soil invertebrates, will be transferred to the food web. To our knowledge, most of the literature focused on the MP and NP transfers in aquatic food webs (Wang et al., 2019; Benson et al., 2022 for a review). The counterpart of these studies are scarce in terrestrial food webs, as pointed out by Wang et al. (2022b). While trophic transfer

of these plastics has been demonstrated (see Chae and An, 2020), the consequences of this trophic transfer to communities remain to be explored.

MP and NP contamination poses a significant threat not only to terrestrial invertebrates, but also affects soil health which is equally crucial for numerous ecosystem functions, thereby presenting potential lasting effects on biodiversity and ecosystem services (Browne et al., 2013; Galli et al. 2022). For instance, this can occur when MP contamination modifies the soil's physical framework, detrimentally influencing water dynamics (Jazaei et al., 2022). Specifically, the infiltration of MP and NP can lead to a substantial decrease in soil porosity, which hinders soil in its ability to retain moisture and facilitate the filtration of water (Guo et al., 2022). Consequently, this alteration in soil structure could hamper the soil's inherent capacity to hold and purify water efficiently, impacting not just plant growth but also groundwater quality (Keesstra et al., 2012; Rabot et al., 2018). A better comprehension of the effects of MP and NP on structure and water-holding capacity of soils is needed, and this requires additional research efforts.

Additionally, MP may pose an interference with the activity of soil microbes responsible for vital processes such as nutrient cycling and the decomposition of organic matter. The disruption of these microbial activities by microplastics impedes the breakdown of organic substances and the natural cycle of nutrients, leading to diminished soil fertility (Wang et al., 2022c; Kumar et al., 2023). NP can then be absorbed by vegetation (as shown in laboratory experiments), which could then be consumed by invertebrates and re-enter the food chain (Chae & An, 2020). Trophic transfer of NP, as well as MP, to herbivorous organisms is still unknown and urgently needs more investigation (Wang et al. 2022d).

5. The way forward for improved understanding of the ins and outs of the Plasticene era

So far, studies have used artificially produced MP and NP. However, such artificially synthesized particles do not reflect the physicochemical characteristics of the plastic debris polluting the environment (Agathokleous et al., 2021; Rozman and Kalčíková, 2021). MAP, MP and NP present in the environment are typically polydisperse and weathered, whereas laboratory-synthesized particles are monodisperse, smooth, and have spherical or ovoid shapes. Collecting and isolating ecologically relevant NP fragments from the environment remain difficult, leading many studies to rely on artificially produced NP. To better understand the fate of NP in soils, and their impacts on organisms, we need to develop more realistic experiments and models that accurately reflect the characteristics of environmental NP. For this, future studies must consider the toxicity of various shapes of MP and NP. Indeed, He et al. (2023) suggested that randomly-shaped NP can induce a different, or even a stronger, toxicity than sphere-like ones on the earthworm *Eisenia fetida*. Hence, there is an urgent need for data on the effects of NP of environmentally realistic shapes and structures, their additives with potential endocrine disrupting effect, and the cocktail effects in case of adsorption of other pollutants on soil fauna. Dose-response effects of NP, including effects of low chronic concentrations, on life history traits and ecotoxicological responses of invertebrates also need to be studied as effects have been only reported for high concentrations (Sanchez-Herandez, 2021).

In the context of the rapidly changing climate, another emerging concern is the temperature that may affect the interactions between nanoparticles and soil organisms (Boyle & Örmeci, 2020). Temperature can affect how pollutants are absorbed and metabolized by insects, and warmer temperatures can increase the risk of toxicity (Buchwalter et al., 2003).

To address these issues, we need more integrated studies that consider the complexity of environmental exposures and temperature effects. This type of research is crucial for shedding new light on these topical environmental issues and for a better

understanding of the cross-toxicity of plastic nanoparticles and their co-contaminants. Boots (2022) emphasized the need to better understand impacts and underlying physiological and molecular mechanisms. Future research must also consider higher organization levels, such as communities, including different trophic levels, including assessment of micro- and nanoplastics effects on human health (as reviewed by Xu et al., 2022). Moreover, considering environmental realistic scenarios in field studies remains a scientific gap. To our perspective, research contributing to address the following questions are crucially needed:

1. Micro- and nanoplastic physical perspectives: are there differences in the fate of plastics in the environment as a function of the nature of the polymer or the weathering state of the debris? What are the effects of soil parameters on plastic dynamics in soils? Can a standardization of sampling and analytics be achieved concerning particle identification, declaration as volume/size, density separation?
2. Organismal perspectives: what are the phenotypic (life history and performance traits,) and physiological impacts (metabolism, energetic and redox status, endocrine and inflammatory responses) of exposure to MP/NP? Are the responses dependent on NP size, type (single or mixed), concentration, weathering? What are the long term and transgenerational impacts of the ingestion of MP or NP, and their co-contaminant? Are there additive, synergistic, or antagonistic interactions between NP, additives, and pesticides?
3. Exposure perspectives: what are the effects of exposure modalities: chronic/acute, cocktails (additives or environmental pollutants), confounding factors? In particular, how does temperature modulate the observed effects on life history traits of parental and offspring generations?

4. Chemical perspectives: How is environmental fate impacted by environmental conditions? How is the fate, transport and bioavailability of NP in soil depending on both plastic and soil properties/types? How is the impact of MAP, MP and NP on soil properties and functioning depending on plastic properties/quantities? How can large scale field-surveys be conducted to add valuable data, also for modeling?
5. Ecosystem perspectives: How are MP and NP transferred through ecological interactions in the food web and thus affect ecosystem services, ecosystem stability and ecosystem resilience (as suggested recently in plant-pollinator interactions; Shah et al., 2023)? Another complex question concerns the mutual interaction/direct - indirect impact via soil microorganisms (bacteria and fungi), which play a crucial role in the soil, with consequences for ecosystem processes and services such as water dynamics, plant growth, crop yield etc.
6. Mitigation perspectives: How can we mitigate the long-term and transgenerational effects of MP and NP contamination? Future strategies need to focus on reducing plastic usage and improving waste management practices globally (Kiran et al. 2022). Additionally, promoting the development and use of biodegradable materials can serve as an effective measure to decrease the accumulation of microplastics in soil environments, safeguarding ecosystem health for future generations.

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Declaration of interest statement:

The authors declare that they have no conflict of interest.

Figure captions

Figure 1. Transformation, transfer and transport of nanoplastics in soils.

Figure 2. Effects of nanoplastics at different organizational scales. These effects are linked to various factors of the polymer.

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Fig 1

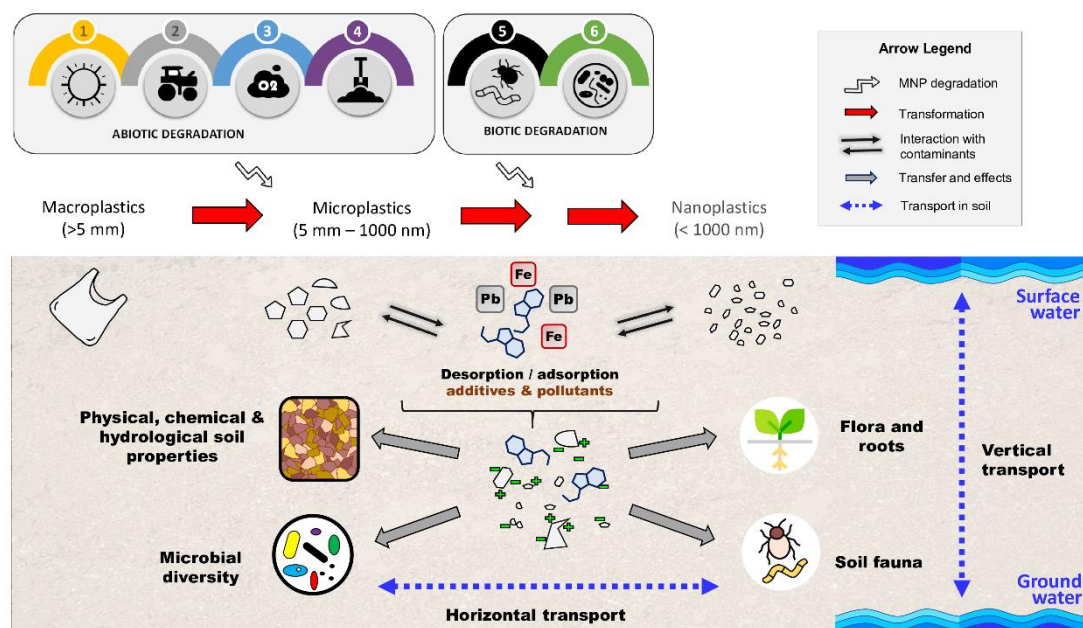
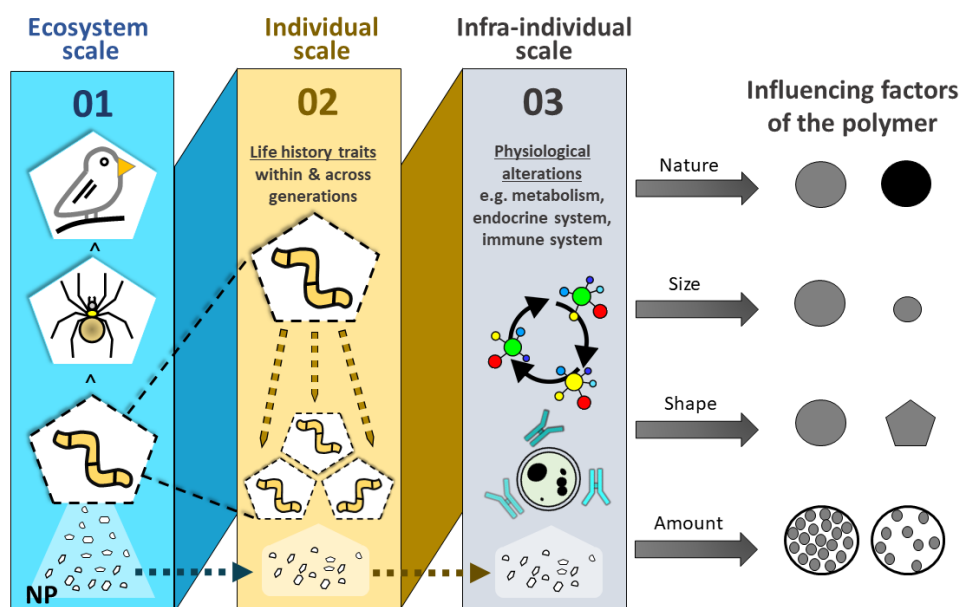
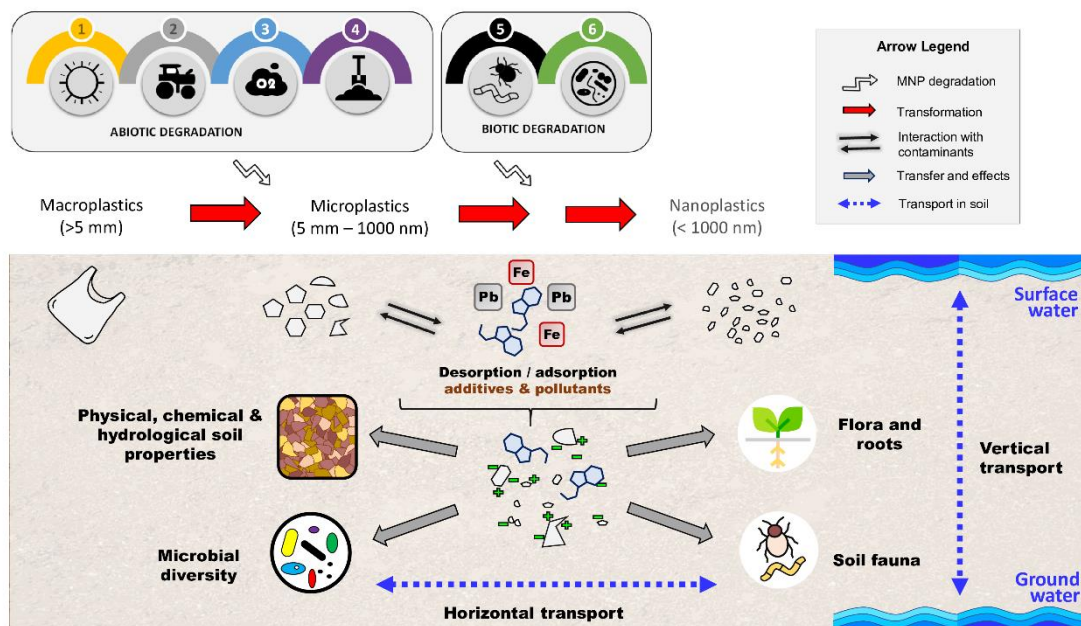


Fig 2



Graphical abstract



Highlights (3-5 bullet points)

- research on micro and nanoplastic must consider environmentally realistic scenarios
- our knowledge of impacts and fate of plastics in the environment must be improved
- More research revealing the small-sized plastics on living organisms are required
- Scaling the impacts at different organizational levels is critically needed