Microplastics and Nanoplastics

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Mind the gap: forest soils as a hidden hub for global micro- and nanoplastic pollution

Collin J. Weber[1*], Matthias C. Rillig[2] and Moritz Bigalke[1]

Abstract
Global plastic pollution has become a major concern because of its effects on environmental and human health. A major fraction of environmental plastics is likely stored temporarily within terrestrial soils. However, even though forests represent the third most common type of land cover on Earth, almost nothing is known about plastics in forest soils. The atmospheric transport of micro- and nanoplastics provides ample opportunity for forest canopies to intercept plastic particles. These plastic particles, together with local plastic sources like litter and items used in forest management, eventually reach forest soils. In this paper we discuss the potential role of forest soils as a hub within global plastic cycles; transport processes from the atmosphere to the soil; and the integration of plastics into forest material cycles. Taken together, plastic in forests could have a major impact on sensitive ecosystems, economically important functions and global environmental plastic budgets. We also develop a roadmap for further investigation into plastics in forest soil systems.

Keywords Atmospheric transport, Canopy intercept, Plastic cycle, Turnover, Ecosystem, Organic soil

Introduction

In recent years plastic has been recognized as a contaminant of global concern [1], and increasing plastic emissions to the environment [2], poses risks to biota and ecosystem functions [3, 4]. The environmental impact of plastic can stem from the disturbance of environmental systems (e.g., soils structure) [5], from effects on biota through plant-uptake or ingestion by animals, and it can have negative consequences for plant-performance and human health [6–9].

The assumed global extent of environmental plastic pollution is based on two factors. Firstly, human-made plastic products are used globally, and the production of such materials has increased exponentially within the last seven decades [10]. As plastics can be released into the environment anywhere and at any point during the product value chain [11], a global extent of plastic release to the environment is expected. Major release processes include the spread of litter [12]; the disposal of waste [13]; the application of plastics to building materials and paints [14], [15]; the use of personal care products [16], agricultural plastics and agricultural fertilizers [17]; and tyre wear abrasion [18]. Micro- (5000–1 µm) and nanoplastics (<1 µm) [19] (MNPs) are now understood to be particulate contaminants that pollute all environmental matrices, including water, ice, soil and air, and can reach the remotest areas on Earth [20–23].

However, the claim that plastics are a ubiquitous pollutant is underpinned by data with limited spatial representativity [20]. Forests are a key type of terrestrial ecosystem on Earth, covering over 38% of global land surface [24], yet forests and their soils are rarely considered in MNP research. Forests are complex ecological systems in which trees are the dominant life-form [25].

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In cool-latitude regions, boreal forests with mainly conifers are the dominant forest type. High-latitude climates have mostly temperate forests with a mix of conifers and broad-leaved deciduous trees, and humid climates have tropical forests with evergreens [25]. To date, two studies have found microplastic (MP) concentrations between 160 and 640 particles kg^{-1} in three single forests worldwide [26, 27]. It is important to note that it is difficult to directly compare between studies due to the different analytical method applications. For method details of the studies see Table S1. In contrast to the comparatively large number of MNP studies conducted on arable lands and soils [20], our knowledge of MNP abundance, processes and risks within terrestrial ecosystems is clearly limited by a lack of forest data (Fig. 1).

Forests and forest soils occur in all climate zones where vegetation growth is possible [25]. In general, forest soils can be differentiated from other terrestrial soils by the growth of trees, the lack of agricultural uses and the presence of specific biological material cycles that differ depending on climate [29]. Forest soils are often more acidic, resulting in higher soil organic matter content in litter layers, and have limited fertility because more fertile land is often already used for agriculture.

There are several reasons why so little is known about MNPs in forest and forest soils. In general, it is expected that forests would have lower concentrations of MNPs than agricultural or urban areas as there are fewer direct input pathways. Furthermore, even though forests across the globe perform important ecosystem functions (e.g., carbon storage, provision of habitat) that produce great economic value [30], human connection to forests is less direct than to agroecosystems where food is grown. Finally, the organic soil horizons in forest [31] are distinct from other terrestrial soils, leading to issues with the methodology of MNP extraction and analysis [32].

Evidence of MNPs within marine, aquatic and arable terrestrial ecosystems underscores the importance of MNP transport processes between these ecosystems. Transport processes within the aquatic environment are comparatively well-studied [33–35], showing transport pathways from terrestrial environments to marine environments via freshwater systems [36–39]. In addition, there is an increasing number of reports on MNP transport within the atmosphere [40, 41]. MNPs have been found in air and dust samples, leading to the recognition of short-distance wind transport and long-distance atmospheric transport for MNPs [42–44].

Atmospheric MNP transport, redistribution and deposition can take place anywhere, resulting in MNP presence in even the most remote locations [45]. We therefore believe that forest ecosystems have an important role in atmospheric MNP transport; forests are generally known for their filter effect on atmospheric gases [46] and aerosols [47]. Could forests and forest soils thus have an important role in the global plastic cycle, defined as "the complex movement of plastic materials between different abiotic and biotic ecosystem compartments" [48]? Could

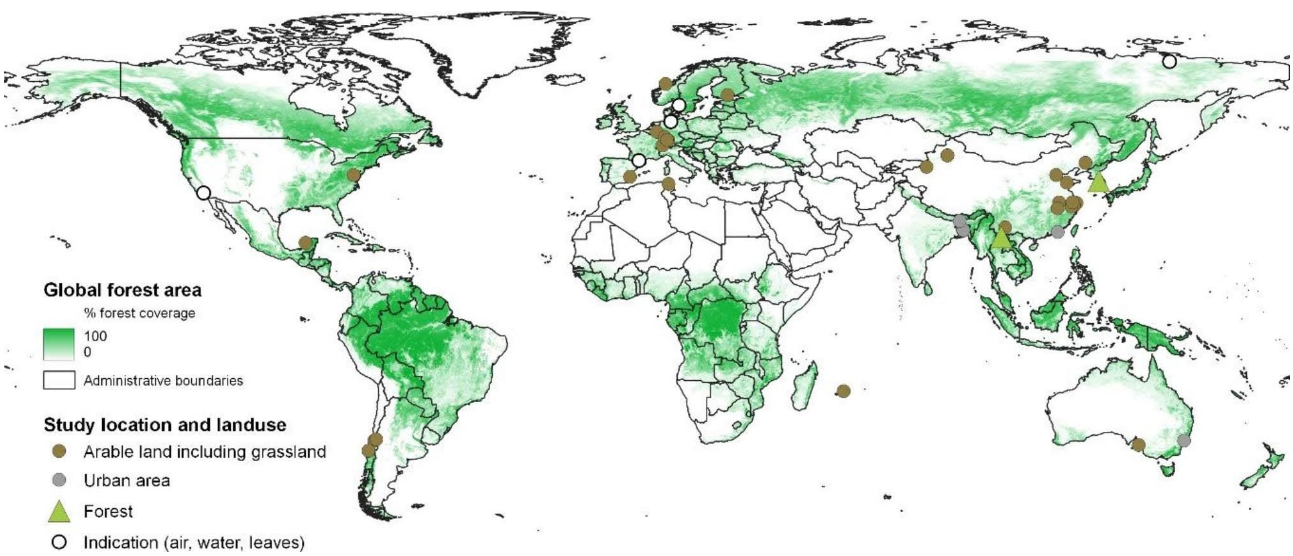

Fig. 1 Global extent of forest area and worldwide case studies on microplastics in soils. The global land area covered by forests with a tree canopy hight > 5 m was 40.2 million km^2 in 2020. Global forest cover distribution includes large contiguous forest areas in all climate zones. Worldwide, case studies conducted on microplastics in soils between 2016 and 2022 have a clear focus in Europe and eastern China. More than 75% of microplastic case studies have been conducted on arable lands, including on croplands, grasslands and plasticulture. Research indicating the presence of MNPs in forests have included studies on forest air, water and tree leaves. Global land cover data from Frontiers | The Global 2000–2020 Land Cover and Land Use Change Dataset Derived From the Landsat Archive: First Results (frontiersin.org), global forest cover data from Tree cover (2000) | Global Forest Watch Open Data Portal and global microplastic case study data from Weber and Bigalke (2022) [28]

forest soils be an underappreciated link between atmospheric MNPs and terrestrial MNPs? In this paper we propose that forests are a hidden hub within the global plastic cycle. Furthermore, we discuss potential processes of plastic trapping by forests, MNP turnover in forest soils, and effects of MNPs on forest ecosystems, as well as implications for further research.

Forest plastic trapping processes

To determine whether forest soils could be a missing hub of global plastic pollution, indicators for MNP trapping processes in forests must be clarified. Until now, the presence of MNPs has been measured directly only at three sampling points located in forests worldwide [26, 27]. Those initial studies refer to atmospheric transportation and the deposition of MPs as the source. Indirect indicators at the regional scale are attained by the detection of MNPs within forest ecosystems, not including soils. Atmospheric MNP deposition in remote or near-urban forests occurs with daily deposition rates of 331–512 particles m^{-2} [44, 49] (Table S1). Additionally, the presence of nanoplastics (NPs) at an average concentration of 563 $\mu g\ l^{-1}$ in lakes and streams within northern hemisphere forests can be traced back to aerial atmospheric NP deposition [39]. Finally, the first direct assessment of MPs at up to 25 p cm^{-2} on urban tree leaf surfaces allowed for the transfer of known particulate matter comb-out effects of trees to MNPs [50] (Table S1).

Extrapolating known processes of particulate matter to MNPs, the whole vegetative surface may be able to trap MNPs reaching the forest via atmospheric transport [47]. MNP deposition on tree leaves can take place via wet deposition, including rain, snow and mist; via dry deposition as direct particulates; or via occult deposition in cloud droplets [51]. As such, all deposition processes depend on the structure of tree canopies and therefore on the tree species in a forest [52]. Based on studies of organic compounds within NP and small MP size ranges, the particle interception and retention on the leaf surface depend on tree leaf characteristics (e.g., roughness, hairiness, orientation), cuticle chemical composition (e.g., individual wax constituents) and cuticle structure (e.g., thickness, alteration, wax crystals) [49, 53].

Canopy-trapped MNPs can reach forest soils via liquid transport by throughfall or stemflow and can be transported via leaf litter [52] (Fig. 2). Therefore, MNPs intercepted by the forest canopy first arrive and accumulate within forest organic soil horizons (Oi, Oe, Oa) and then reach mineral soil after the leaching and turnover of the organic horizons.

Plastics in dynamic turnover cycles

If MNPs are trapped by a forest canopy and accumulate within the organic soil horizons, their fate will be affected by dynamic biogeochemical turnover processes. A major process affecting the fate of MNPs and their transport to deeper mineral soil layers is the decomposition of organic soil horizons as part of the biological cycle. MNPs deposited at the soil surface (e.g., Oi) will be found in Oa horizons after several years, solely through transformation of the soil horizon; this would not involve transport processes. Therefore, depending on the thickness of the organic horizon, MNP research should examine forest soils that are deeper than the uppermost 10 cm of topsoil. Additionally, vertical transport processes by leaching or bioturbation [8, 54, 55] will also foster the translocation of MNPs from the organic soil to the mineral soil. Within the organic or mineral soil, the following processes will further affect the fate and properties of MNPs: MNP fixation within soil aggregates (immobilization of MNPs) [55]; the vertical and lateral transport of MNPs (mobilization of MNPs) through leaching within pore spaces [54] or through bioturbation [56]; and MNP ageing and degradation from biogeochemical processes in the absence of UV radiation and photooxidation (chemical changes and disintegration of MNPs) [7, 57–59] (Fig. 2).

MNP ageing may be different in forests compared to agricultural sites, where most of ageing studies have been conducted so far, due to the different enzymatic potential of the soil microbiome, the soil animal communities (e.g., micro-arthropods) and the mostly lower pH conditions. Forest soils on average contain microbiomes better suited to the breakdown of persistent biopolymers that many other ecosystems, and this can enhance polymer degradation by breaking the macromolecules into smaller products, which are then bioavailable and can be further utilized [60]. Microorganism groups which use wood as an energy source are common in forest soils. White-rot fungi, brown-rot fungi and ligninolytic bacteria all belong to such groups and can contribute significantly to plastic degradation by producing extracellular enzymes such as lignin peroxidase, manganese peroxidase, versatile peroxidase and multicopper oxidase laccase to decompose lignin and some plastic polymers [61]. Other enzymes can change MP properties (e.g., hydrophobicity and crystallinity) and thus can increase their potential for degradation by other processes (e.g., hydrolysis). Enzymes like esterase can increase enzymatic hydrolysis [62]. Cutinases can hydrolyse cutin, which is found in the plant cuticle of many trees [63, 64] and are also able to hydrolyse the ester bonds in PET and PUR [65, 66]. As such, we assume that MNP ageing may be different and is likely faster in forest soils than in other ecosystems. Consequently, also the leaching and therefore release of additives (e.g., pigments, stabilizers or flame retardants) from aged plastic particles, could contribute to an enhanced chemical exposure of forest soils and possible bioaccumulation of toxic chemicals [54].

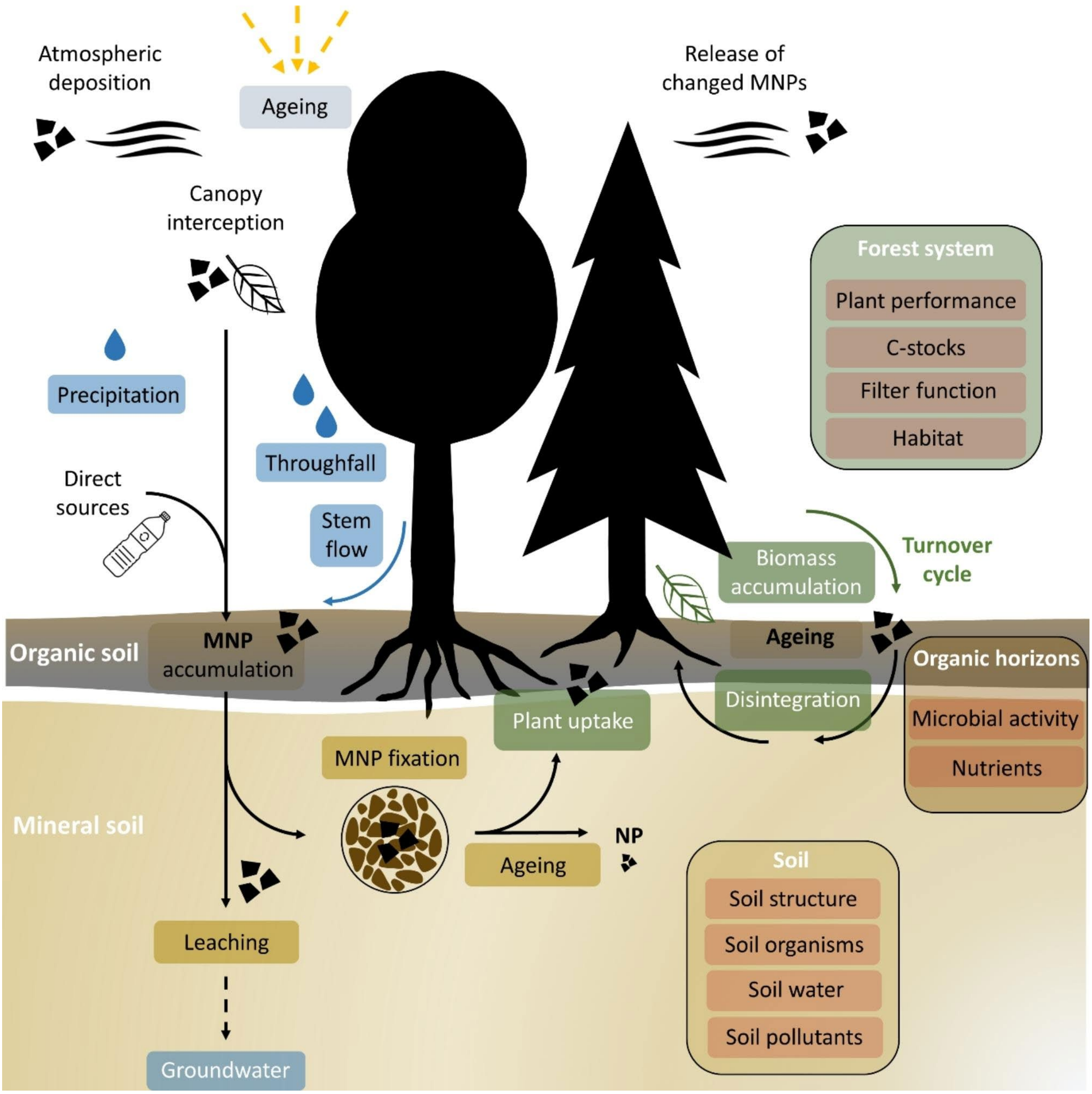

Fig. 2 Forest trapping function with micro- and nanoplastic turnover in forest soils. Micro- and nanoplastics (MNPs) can reach forest systems via atmospheric deposition. MNPs transported by the atmosphere are intercepted by the forest canopy. Natural processes like leaf litterfall, rainfall and stem flow transport MNPs to the soil surface and directly incorporate them into organic soil horizons. Direct anthropogenic sources like litter or forest management practices further contribute to plastic pollution in organic horizons. MNPs accumulate and age within organic soil layers, leaching or mixing into the mineral soil and are ultimately discharged into the groundwater. Within organic and mineral soil MNPs can be aged by biogeochemical processes. Once incorporated within the forest soils, MNPs are introduced into the natural turnover processes of biomass accumulation, disintegration and plant uptake. MNPs in forest soils likely negatively affect forest soil structure, organisms, and soil water movement and capacity. Plastic particles can release additives from their interior volumes, and can have combined effects with other soil pollutants (e.g., sorption processes) [4, 7]. Furthermore, MNPs can affect soil microbial activity and nutrient availability within organic horizons, causing potential ripple-on effects in the forest system [54]

In addition to MNPs affecting processes in the soil, MNPs may also be able to leave the forest soil system. Mobile MNPs, can leach into deeper soil layers and exit the soil for groundwater or surface water [54]. Changed surface properties of plastic particles such as enhanced surface area, negative surface charge or increased roughness, caused by ageing processes will furthermore effect transport behaviour by e.g., hetero-aggregation with soil colloids in mineral soil or sorption on organics in organic soil horizons [54, 62]. Because of the comparatively high transpiration rates of trees compared to other vegetation [67], which causes higher soil water uptake, trees could have relatively high MNP uptake.

Recent research has shown that MNP plant uptake may depend on plant properties and MNP features, especially MNP size and shape [68]. Trees can take up MNPs smaller than 10 µm in their roots and transport them to shoots [69, 70], even though the rates at which this occurs are unclear for adult trees growing in a forest soil. The uptake and transport of MNPs to the shoots implies that MNPs can integrate into the complete biological cycle of forest from deposition, over litterfall and plant-uptake. In detail, MNPs can be deposited on tree leaves and reach the organic soil horizons via litterfall and liquid transport, passing through the forest mineral soil and being taken up by trees; MNPs can also reach the organic soil horizons again within plant material (Fig. 2), illustrating the potentially complete integration of MNPs into the biological and geochemical turnover cycles and the material flows of forests.

Impacts by different soils

The global core areas of forests, which have contiguous forest coverage of over 50%, are areas within the tropics (e.g., Amazonian Basin) or the northern boreal areas (e.g., Siberia). Based on the FAO Soil Map of the World [71] (Fig. 3), forest soils can be classified according to the Reference Soil Groups (RSGs) [72] as tropical areas with dominant Ferralsols and Acrisols and with subdominant Kastanozems, Gleysols, Histosols and Nitosols; or as temperate areas with a mixed pattern of dominant Cambisols, Lithosols, Podzols and Luvisols and with subdominant Fluvisols, Gleysols and Acrisols (Fig. 3). Thus, the most abundant forest soil types are different from the soil types in agriculture that have previously been investigated [28]. Accordingly, MP transport and turnover processes will be different. For example, Podzols accumulate thick organic horizons because of the acidic pH, while Ferralsols have high turnover that mostly results in very thin organic layers and quick incorporation of MNPs into the mineral soil [73, 74]. Additionally, MNP ageing and disaggregation through biogeochemical processes would be much slower with the lower microbial activity in Podzols; these processes would run faster in Ferralsols as they have higher microbial activity promoted by higher soil temperatures and moisture [61].

Effects on forest soil systems

The possible effects of MNPs within forest soil systems can be differentiated as effects on the organic soil

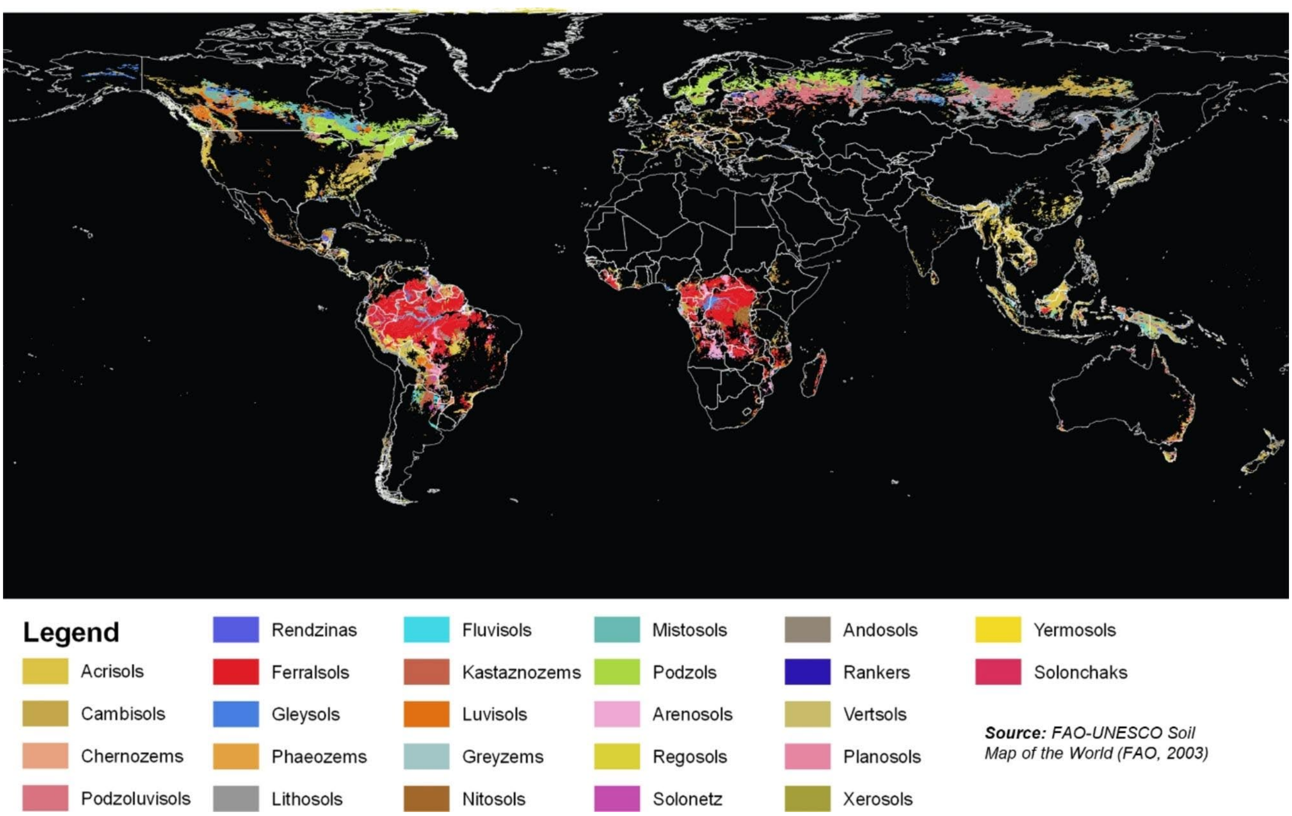

Fig. 3 Global core forest areas and related soils. Soils according to the FAO Soil Map of the World [71]. Global core forest areas have canopy coverage > 50% for each 18.5 × 18.5 km [2] sample area and do not have inland waters. Forest data from Tree cover (2000) | Global Forest Watch Open Data Portal and soil data from Digital Soil Map of the World (fao.org)

horizons, the mineral soil, or the forest systems, which includes plants and other organisms. In general, these effects will depend on MNP properties, forest soil properties, vegetation and soil organisms. The current lack of data and lack of method harmonization hinders any assumptions about MNP properties in forest soils, in contrast to arable land soils. When considering atmospheric deposition as the major input pathway for MNPs, we can only assume a comparatively small MNP size, as well as the preponderance of fibres already present at system entry [42, 49] and possibly aged MNPs through prolonged atmospheric transport [75]. The most directly applicable information that can be transferred from work in agricultural soils relates to effects on the mineral soil, as discussed in the current literature [5, 55, 68]. To summarize, there are effects on soil structure (e.g., the decrease in bulk density and aggregate strength [76, 77]), soil water dynamics (e.g., increased water infiltration [78]), material flows and cycles (e.g., hindered soil microbial processes [79–81], macroinvertebrates activity [8, 80] or plant growth [6, 7]) and sorption and desorption processes with other soil pollutants (e.g., trace metals and organic pollutants [82]).

To date, the effects on forests organic soil horizons are less directly transferable from work on other soils. However, those horizons can be considered an active layer due to enzymatic and microbial activity, which decompose the organic material and constitute a major part of the organisms living there [31]. The negative effects of MNP on organisms' activity, lifetime and reproduction have already been examined; those impacts can be assumed to play a role for organic soil horizons, as well. Influences on litter quality and litter decomposition under the presence of MNPs could trigger widespread effects on entire forest systems [79, 81, 83, 84].

All of these effects depend strongly on the MNP concentrations and MNP features present. A rough estimate based on available MP data from air samples in temperate forests [44, 49] (Table S1) shows a possible median deposition of 23,269 p kg^{-1} in forest topsoils (0–10 cm) after 20 years. This assumes a soil bulk density of 1.2 g cm^{-3} and no MP output (e.g., migration). In comparison to global MP averages in soils of 1167 p kg^{-1} and maxima of 13,000 p kg^{-1}, not restricted to comparable MP extraction and analytical methods, forest soils might contain MP concentrations in the upper range of known particle-based concentrations [20], while the mass-based concentration could differ as we would expect high numbers of small and light-density MP through atmospheric deposition, as in agricultural soils with direct local inputs. This assumed amount of MP in forest soils could be within the range that causes effects on soil systems [85, 86]. Trees are the major plant species within forests, so any and all effects on soil structure, water availability and nutrient availability could impact tree growth, especially in younger growth stages, as well as general performance and health. Possible effects on forest systems due to the presence of MNPs in considerable doses and the inclusion of MNPs within turnover cycles could include negative impacts on forest plant performance and therefore on material flows (e.g., C-stocks), forest filter functions and forest habitat functions [29].

A road map for research on MNPs in forests

The global extent of forests and their environmental functions highlights the urgent need for focussing research on MNPs in forest soil systems. The global fate and transport of MNPs, especially the environmental risks of MNPs for forest soil systems, must be understood. For this purpose, and with a focus on forest soils, we propose a road map for building a basic knowledge base on the "forest plastic hub" (Table 1). In this road map, we suggest research that should be conducted on different forest types (boreal, temperate, tropical), as MNP processes and impacts will vary along climatic gradients and resulting forest properties. For soil related MNP research, we advocate for a widening of focus when investigating soil systems. Though understanding arable soils is important for global food security, MNP research on underrepresented soil systems, like forest soils, is necessary to develop a complete understanding of MNP global cycling and analyse the implications for such cycles. Our suggested toolbox includes a two-pronged approach: we need to learn more about the scale of the problem by employing observational approaches in the field with data on global MNP concentrations in forest soils, and we need to complement these with targeted experimental research on microcosm systems. Work should then progress to mesocosm studies where larger trees can be studied. This would, however, require significant logistics and time commitments.

Conclusions

In this paper, we demonstrated that forests are a blind spot in our understanding of terrestrial MNP pollution. Forest soil and ecosystem structure, as well as ecosystem management, differ drastically from other ecosystems in which the effects of MNPs have been studied, so we expect there will be differences in fate and effects and new insights into MNPs. We thus urge the community of scientists studying MNPs, soil science, biogeochemistry, ecotoxicology, pollution ecology and global change biology to embrace the inclusion of forest systems in their future research plans. Finally, the role of forests as interceptors of atmospheric plastic pollution could have important implications for MNPs in the atmosphere since forests serve as filters in this context.

Table 1 *Road map for building basic knowledge of the forest plastic hub*

Research needs	Suggested approaches
Global data for MNP concentrations and characteristics in forest organic and mineral soils	*Forests and their soils are very heterogenous and cover a large share of global land surface.* • We suggest researchers attain representative sample materials from poorly decomposed organic layers using spatially representative sampling and larger sample volumes, as well as subsequent sample deviation. • We suggest developing a suitable extraction method to access MNPs concentrations and characteristics in forest soils and analyse MNPs in high organic little decomposed horizons via state-of-the-art analytical methods like μFTIR for > 20 μm MP, μRaman for < 20 μm MP and > 500 nm NP as well as py-GC-MS for < 500 nm NP. • We suggest holistic MNP analysis and monitoring within different forest systems in different climate zones to develop global MNP budgets for forest soil systems.
MNP inputs, cycling and outputs in forest systems	*Forest systems are complex; there is little known about the input and output of MNPs, as well as their incorporation into biological and geochemical turnover cycles. There is a lack of global data for dry and wet deposition in forests via throughfall, stem flow and transport with litter traps, soil mixing and leaching to groundwater systems, and plant-uptake.* • We suggest tracing MNP pathways in experimental field sites. Atmospheric deposition (via air and leave sampling), water samples (rainfall, stem flow, groundwater), and soil and plant material (leaves, litter) should be analysed to assess MNP inputs, cycling and budgets. • We suggest investigating MNP uptake in common tree species under controlled laboratory and field conditions through state-of-the-art methods (e.g., metal, fluorescent or ^{13}C spiked MNPs in combination with imaging techniques).
The fate of MNPs in forests, organic soils and mineral soils	*Within forests and forest soils, the environmental fate of MNPs (e.g., disaggregation, ageing) are different from those in agricultural soils, mainly due to variable UV radiation, microbial activity and the absence of physical disturbances like ploughing*: • We suggest performing MNP disaggregation, soil colloid/aggregate integration and ageing studies under controlled laboratory conditions via forest organic and mineral soil microcosm experimental setups. • We suggest assessing the MNP degradation status within forest systems by analysing environmental MNP surface characteristics in forests via state-of-the-art methods (e.g., SEM).
Effects of MNPs on forest soil physio-chemical properties	*Studies on the effects of MNP on soil physiochemical properties have been conducted mainly for agricultural soils. As the soil management and structure is very different in agriculture and forests, the effects must be investigated for forest soils, separately.* • We suggest performing controlled laboratory and field experiments with realistic doses of MNPs in forest soils (derived from measurements campaigns; see above) to study the possible effects of MNPs on soil structure, soil water dynamics, and soil pH.
Effects of MNPs on forest (soil) biodiversity	*Forests harbour organisms which are quite different from those in agroecosystems, partially as a direct consequence of different ecosystem properties. It is thus vital to examine any effects MNPs may have on soil biota (and perhaps beyond) in controlled experiments involving mesocosms or microcosm setups, as well as in the field.* • We suggest that experiments examine effects to the organic layer, as well as the mineral soil. Any effects should be tightly linked to changes in soil physicochemical properties. Given the role of fungi in the degradation of persistent organic matter, such studies should include and perhaps initially focus on fungi. • We suggest that plant community effects be included as well, especially for forests featuring a pronounced understory layer.
Effects of MNPs on turnover cycles in forest systems	*The presence of MNPs within forest turnover cycles could impact various biological cycles and plants and could therefore affect forest ecosystem functions.* • We suggest investigating interferences of forest soils biological activity and its influence on biogeochemical cycles in the presence of MNPs, with realistic doses under controlled conditions in micro- and mesocosm studies. • We suggest performing controlled experiments that investigate the possible effects of MNPs on litter quality, litter decomposition, humus formation and material turnover processes (e.g., carbon, nutrients).

List of Abbreviations

MNP	Micro- and nanoplastic
MP	Microplastic
NP	Nanoplastic
UV	Ultraviolet light
PET	Polyethylene terephthalate
PUR	Polyurethane

Supplementary Information

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Supplementary Material 1

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Authors' contributions
Conceptualization: Collin J. Weber, Matthias C. Rillig and Moritz Bigalke; Writing – Original Draft and Review and Editing: Collin J. Weber, Matthias C. Rillig and Moritz Bigalke; Visualization: Collin J. Weber. All authors approved the manuscript.

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Data Availability
All data generated or analysed during this study are included in this published article.

Declarations

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