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# Getting occurrence, distribution, fate and detrimental effects of microplastic in forests into focus: expectations and challenges

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## 1 Introduction

Micro-(nano-) plastics (MNPs; MPs <5 mm; NPs <1 μm) have been widely distributed in the environmental compartments, and potentially threatened the ecosystems (Wu et al., 2022a; Wu et al., 2024a). Since they were firstly reported in 2004, large quantities of studies have investigated their occurrence, distribution, and potential risks in aquatic systems (Thompson et al., 2004; Wu et al., 2022b). A agreement achieved that the contained MNPs are mainly originated from the terrestrial inputs, including the water runoff, groundwater exchange, etc (Kumar et al., 2023). Thereafter, a growing body of studies concentrated on investigating the content, fate and detrimental effects of MNPs in terrestrial environments (Zhu and Huang, 2025). Newer data suggest that MNPs are moving from the soil to the plant, as demonstrated by their presence in lettuce (Li et al., 2020), carrot (Dong et al., 2021), wheat (Li et al., 2020), and rice seedlings (Liu et al., 2022), raising significant concerns on their negative consequences on the farmland. Therefore, more and more attention has been paid on the potential detrimental effects of MNPs on farm products. As a crucial part of agroforestry economics, the safety of forestry products in contrast is often ignored, which caused by not enough information on MNPs occurrence has been reported in recent studies.

Forestry land is also of great importance in ecosystem, covering over 32% of global land surface (Winkler et al., 2021), yet forests and their soils are rarely considered in MNP research. Forests act as the sink of carbon, helps regulating the climate, and provides habitats for diverse for a and fauna. The MNP contamination of forestry land could affect the health of the forestry ecosystem (Weber et al., 2023). Recent study investigate MNPs contamination in 8 forests in Korea and found they were between 20 and 720 particles $kg^{-1}$ in three single forests worldwide (Choi et al., 2021). They further reported that the presence of MNPs can alter soil structure and decrease the fertility, having the potential influences on the growth of trees and the health of forest. Although the related information is still infancy, more and more publications have reported that the uptake of MNPs could biomagnify through the food web and pose risks to wildlifes. Thus, it is of great importance to understand the occurrence, distribution, fate and detrimental effects of MNPs in forests.

# 2 Sources and pathways of MPs in forestry ecosystems

## 2.1 Atmospheric deposition

Atmospheric transport was regarded as a critical route for MNPs contamination in forests (Allen et al., 2019). Anthropogenically generated MNPs from urban/industrial emission sources undergo complex aerodynamic transport processes. These lightweight particles are entrained in atmospheric circulation patterns, with field measurements confirming their presence in precipitation samples from remote alpine regions (e.g., Pyrenees, 2,877 m ASL) at concentrations up to 365 particles/$m^2$/day (Allen et al., 2019). The deposition dynamics encompass both dry (gravitational settling) and wet (precipitation scavenging) mechanisms, with particle form (sphericity, aspect ratio) markedly affecting residence times (Huang et al., 2021). Studies on canopy interception effectiveness indicate that coniferous forests catch more atmospheric MNPs than deciduous trees, attributed to increased surface roughness and wax-mediated adhesive effects (Weber et al., 2023).

## 2.2 Anthropogenic edge inputs

The permeability thresholds in forest buffer zones are increasingly influenced by long-term MNP inputs from adjacent anthropogenic systems. Agricultural matrices contribute large numbers of MNPs annually to various environmental compartments through composite pathways: (1) Degradation of low-density polyethylene mulch films releasing MNPs into the forests (Sintim et al., 2020); (2) Biosolid-amended fertilizers containing up to 286 particles/g dry weight (Naderi Beni et al., 2023); (3) Wastewater irrigation delivering 1.0–2.4 × $10^4$ particles/kg effluent (Wu et al., 2024b). These inputs induce measurable pedological alterations, including the reduction in saturated hydraulic conductivity and the decrease of pH value in topsoil horizons. Field experiments demonstrate MP-soil interactions promote aggregate destabilization through weak hydrogen bonding with clay minerals, exacerbating nutrient leaching losses (Elmholt et al., 2008).

## 2.3 *In situ* generation

*In situ* MP generation in forest ecosystems follows quantifiable weathering trajectories governed by Arrhenius kinetics. Polymeric materials from tourism debris (PET bottles, LDPE wrappers) and logging residues (PP rope fragments, HDPE fuel containers) undergo sequential degradation: Photo-oxidative cleavage, hydrolytic depolymerization, and mechanical embrittlement (Wu et al., 2024c). Accelerated aging tests indicate high-density plastics (e.g., PET) require 8.3 ± 1.2 years for 50% mass loss under temperate forest conditions, versus 2.1 ± 0.7 years for low-density films (LDPE). Secondary MP generation rates peak with particle size distributions skewing towards environmentally persistent 10–100 μm fractions (Cózar et al., 2014).

# 3 Ecotoxicological effects on forestry ecosystems

## 3.1 Soil physicochemical impacts

MNPs systematically compromise forest ecosystems through multidimensional pathways. In soil systems, MNPs have been certified to reduce macroporosity by 15%–30% and water-holding capacity by 18%–25% via structural disruption, while their hydrophobic surfaces amplify contaminant bioavailability (Schefer et al., 2025). Wang et al. (2024) determined the concentration dependent effects of PVC MNPs on affecting the physicochemical characters of soils with various soil textures. The soil texture should be a key issue affecting their pore connectivity, especially for sandy and sandy loam soils. The results may be attributed to the following mechanisms: First, the MNPs could occupy the pore spaces of soil and create disconnected voids, thereby reducing the pore connectivity and effective porosity (Schefer et al., 2025). Second, many types of MNPs are hydrophobic, which could decrease the soil water affinity, thereby disrupting capillary forces that stabilize pore networks (Shafea et al., 2023). Third, the fate of MNPs in soil could also influence its connectivity by inhibiting the soil fauna and adsorbing other chemicals to form MNP-aggregate complexes (Schefer et al., 2025).

## 3.2 Microbial functional changes

Concurrently, sublethal MP exposure suppresses microbial functions: nitrogen-fixing bacteria exhibit 40%–60% reduced nifH expression, correlating with 22%–35% declines in nitrogen mineralization, while arbuscular mycorrhizal fungi show 30%–50% fewer root-colonizing hyphae, impairing phosphorus uptake (Aralappanavar et al., 2024). Metagenomic shifts further reduce extracellular enzyme activity.

## 3.3 Plant physiological responses

Plant physiology is equally compromised—MPs (10–300 μm) adhere to roots via electrostatic forces, reducing absorptive surface area and hydraulic conductivity (Sun et al., 2020), while sequestered $Fe^{3+}$/$Zn^{2+}$ induces micronutrient deficiencies. Leached additives like Di (2-ethylhexyl) phthalate trigger root ROS surges ($H_2O_2$), causing mitochondrial damage and stunting conifer growth (Wu et al., 2022a). Soil invertebrates face acute toxicity: earthworms ingesting 5–20 μm MPs endure gut epithelial damage, reducing cast production by 35%–60%, while collembola suffer 50% mortality and 65%–80% egg reduction at 100 mg/kg MPs (Guo et al., 2023).

## 3.4 Other potential effects

Trophic transfer escalates risks—birds accumulate 12–45 particles/g in gizzards, and tertiary consumers like martens ingest DDT-laden MPs. Critically, MNPs synergize with climate stressors: MNP-contaminated soils desiccate faster during droughts, advancing tree wilting, while suppressed jasmonic acid signaling in oaks increases herbivory. MNPs also lower lignocellulose ignition temperatures, accelerating crown fires, and release toxic acrylonitrile upon combustion, compounding post-fire ecotoxicity (Jin et al., 2024). This cascade of impacts underscores MPs as a keystone stressor in Anthropocene forest decline.

## 4 Challenges in assessing forestry MP ecotoxicity

Comprehensive evaluation of MNP consequences in forest ecosystems is hampered by important knowledge gaps. Current methodological constraints, especially spectroscopic and chromatographic approaches, lack sufficient resolution to quantify nanoplastics (<1 μm) inside organic-rich soil matrix, where humic acids and lignocellulosic chemicals interact with polymer identification. Lack of longitudinal studies—few datasets span decadal durations required to assess MNP accumulation rates against tree lifespans (typically >50 years for temperate species) or legacy soil processes like humification cycles—adds to this analytical limit. Moreover, the complex linkages among MNPs, soil biogeochemistry (e.g., pH-dependent polymer breakdown), and biotic networks (e.g., microbiome-plastic interactions) still cause fragmented knowledge at the level of ecosystems. Addressing these challenges calls for long-term ecological monitoring systems, multidisciplinary integration of advanced characterization tools (such as pyrolysis-GC/MS with isotopic tracing), mechanistic models bridging microbial ecology, polymer science, and forest hydrology to untangle emergent hazards in these complicated systems.

## 5 Recommendations for policy and research

### 5.1 Research priorities

As for MNPs in forest ecosystems, several actions for decreasing MNP threats to forest ecosystems could be discussed as follows: First, it is of great importance to develop standardize microplastic collection process, consistent monitoring protocols specific to forest environments including harmonized methodologies for soil core sampling, canopy particle collecting, and hyperspectral detection of MNPs in organic matrix to produce comparable baseline data. Meanwhile, the ecotoxicological thresholds and species specific resistance can be determined by controlled mesocosm experiments, such as the gradient MNP concentrations from (0.1%–10% w/w), exploring the nutrient or contaminants transferring. In addition, critical research gaps requiring urgent attention on nanoparticle mobility in root systems, polymer-specific adsorption dynamics in humic soils, and co-stressor interactions (e.g., drought or heavy metals).

### 5.2 Policy and community engagement

Scientific insights must inform policy reforms, such as phasing out non-degradable agricultural mulch films (with subsidies for biodegradable alternatives), mandating wastewater treatment upgrades to capture sub-micron particles (prioritizing plants near old-growth forests), and integrating MNP surveillance into protected area management plans (e.g., IUCN Category II forests). Plastic influx can be decreased while promoting stewardship through parallel public engagement projects aimed to communities near forests, such as bilingual workshops on reusable alternatives to single-use plastics and citizen science initiatives for litter audits. Parallel public engagement campaigns targeting forest-adjacent communities—via multilingual workshops on reusable alternatives to single-use plastics and citizen science programs for litter auditing—can reduce plastic influx while fostering stewardship. By synergizing robust science, evidence-based governance, and grassroots behavioral change, this multipronged strategy offers a pathway toward mitigating MNP-driven forest degradation.

## 6 Conclusion

As the pervasive contaminants, MNPs also pose emerging threats to forests despite receiving less attention than agricultural systems. Covering 32% of Earth's land surface, forests act as vital carbon sinks, biodiversity refuges as well as receiving MNPs via atmospheric deposition, anthropogenic edge inputs from agriculture, and *in situ* generation from tourism debris. These MNPs significantly degrade forest health through multiple pathways: they alter soil physicochemical characters, reducing the pore connectivity by occupying pore spaces and increasing hydrophobicity; impair microbial functions; change plant physiology; release hazardous additives; and biomagnify risks through trophic transfer. Synergistic interactions with climate stressors exacerbate impacts, such as accelerated drought-induced wilting or altered fire behavior. The main research gaps still exist as the method limitations in calculating MNPs in organisms and a lack of long-term studies. For over these obstacles, the standardized forest-specific monitoring protocols and mesocosm experiments are required to determine ecotoxicological thresholds for keystone species, policy reforms, and community engagement initiatives to mitigate MNP-driven forest degradation.

## Author contributions

KT: Writing – original draft, Data curation, Writing – review and editing, Validation, Conceptualization. SP: Writing – original draft, Conceptualization, Resources, Investigation. YM: Conceptualization, Investigation, Writing – original draft. PY: Writing – original draft, Investigation. QH: Project administration, Formal Analysis, Conceptualization, Methodology, Supervision, Data curation, Writing – original draft, Software, Visualization, Resources, Writing – review and editing, Funding acquisition, Validation, Investigation. YL: Writing – review and editing, Investigation, Writing – original draft, Supervision, Data curation, Software, Methodology, Resources, Funding acquisition, Visualization, Conceptualization, Formal Analysis, Project administration, Validation.

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## Conflict of interest

Author PY was employed by Suining Runqi Investment Co., Ltd.

The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

## Generative AI statement

The author(s) declare that no Generative AI was used in the creation of this manuscript.

## Publisher's note



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