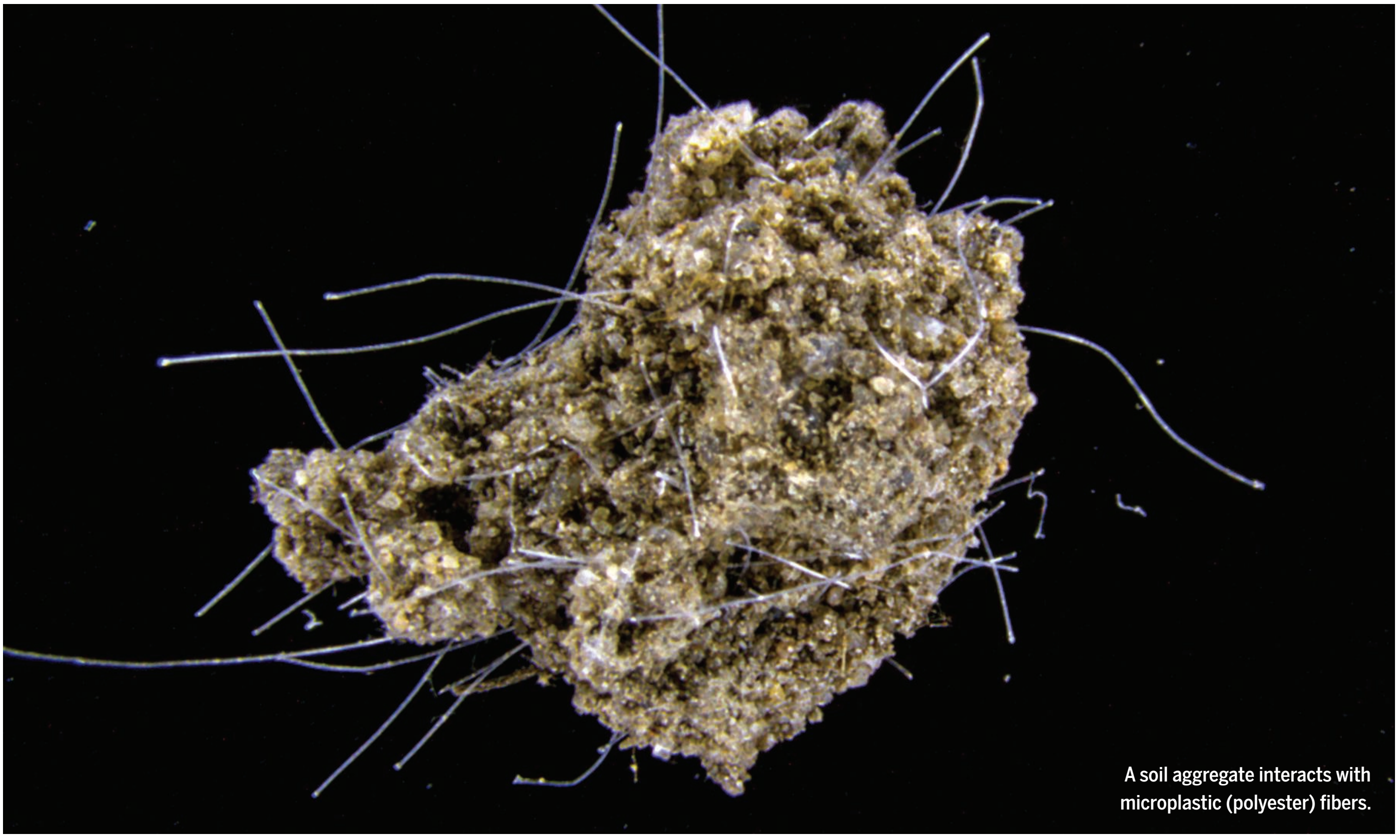

A soil aggregate interacts with microplastic (polyester) fibers.

ECOLOGY

Microplastic in terrestrial ecosystems

Research shifts from ecotoxicology to ecosystem effects and Earth system feedbacks

By **Matthias C. Rillig** and **Anika Lehmann**

Concern about microplastics (plastic particles <5 mm) polluting different environmental compartments is mounting. Research has recently begun to embrace terrestrial systems, having initially focused at least a decade earlier on marine and aquatic ecosystems (*1*–*3*). The early research agenda on microplastics in both aquatic and terrestrial systems was mainly ecotoxicological. It included laboratory tests on individual organisms, often well-established test species (*4*), and also targeted selected soil properties and processes. Such research is necessary to establish baseline mechanisms, which is important because microplastics differ from other pollutants. Many of their effects appear to be mediated by physical parameters, such as particle shape and size, rather than overt chemically mediated toxicity. Moreover, their effects are mostly sublethal or even nominally positive. Although the study of other global change factors has tended to focus at the level of the ecosystem, research on microplastic is only now on the verge of this wider view.

The first step in this direction has been the conceptualization of the "plastic cycle" (*5*, *6*), acknowledging that microplastics can move between different large-scale compartments, including the air, terrestrial habitats, rivers and other freshwater bodies, and the ocean, including its sediments (*7*) (see the figure). The cycle framework places these movements in the context of the pools and fluxes that are inherent to ecosystem ecology. The current challenge is to understand how microplastic flows affect such pools and fluxes in terrestrial ecosystems.

Microplastics are mostly composed of carbon, among other elements. Microplastic addition to ecosystems thus represents a source of carbon independent of photosynthesis and net primary production. This polymer carbon likely has a slow turnover, because the material is mostly inert; however, the behavior and residence time of microplastics in soil are currently unknown. We also do not know the input rate of microplastic-carbon into ecosystems itself, because research hitherto has largely focused on quantifying particle numbers and types, rather than on the microplastic-derived carbon itself. Originally, most of this carbon is of fossil origin, rather than having recently been fixed from the atmosphere. Because of the resistance of microplastic to decomposition, it would be expected to accumulate in soils, where it needs to be accounted for in assessments of soil carbon storage (*8*), a major ecosystem function.

Other effects of microplastics will be indirect and likely depend on particle shape and size. For microplastic fibers, effects on soil aggregation, a key process governing soil structure, are quite well established (*9*). Soil aggregates are the crumbs contributing to soil structure and have a central role in shaping the habitat of soil orga-

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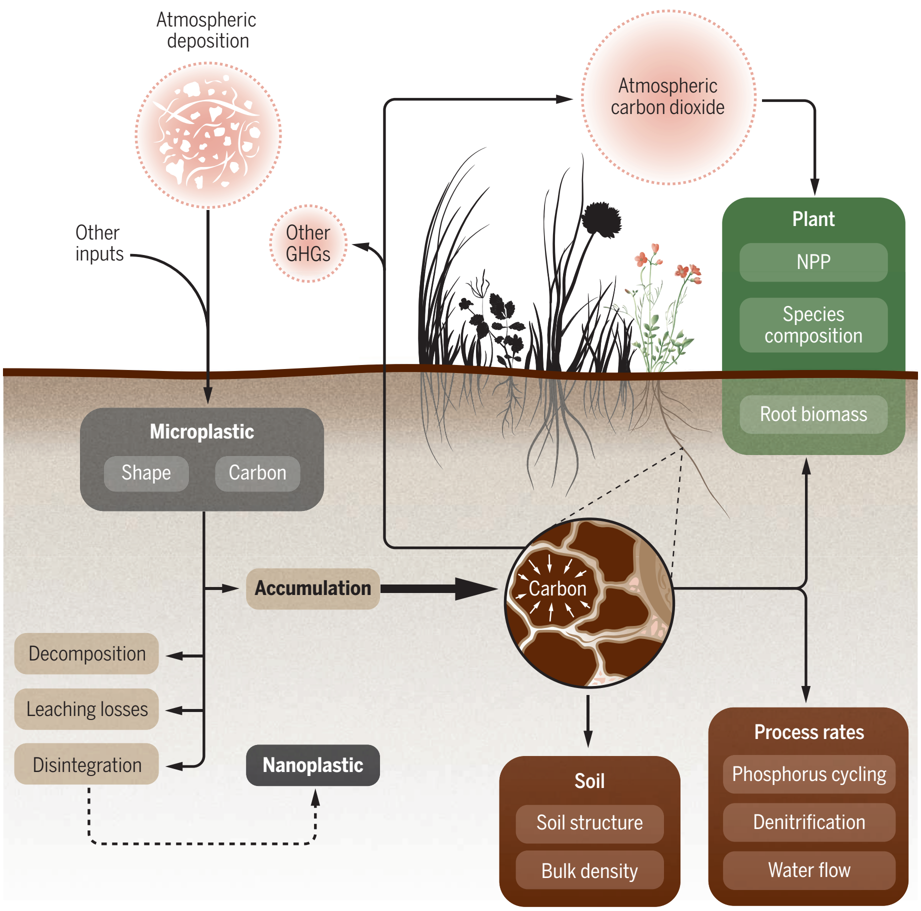
Microplastic fluxes and associated ecosystem feedbacks

Deposition and accumulation of microplastics can affect soil properties, with consequences for process rates and net primary production (NPP), causing feedbacks to the atmosphere, including greenhouse gases (GHGs). So far, nanoplastic has unknown consequences for this system.



nisms. Additionally, carbon compounds are stored within aggregates, where they are physically protected from being rapidly decomposed. Soil aggregates also determine the pore space in the soil overall, in turn influencing movement of gases and water, and the activity of associated microbial communities. A completely different indirect effect occurs because of lower soil bulk density in the presence of fibers. This can lead to enhanced plant growth, probably because roots experience less resistance when growing (*10*). However, negative effects on plants, likely related to plastic additives, are also possible (*11*). Which types of microplastics could promote or inhibit plant biomass production is an important area for future research.

Consequences for other element cycles are more uncertain. Direct effects will likely be minimal, because microplastics contain mostly negligible amounts of nitrogen and phosphorus (even though there are exceptions, such as polyamide). However, alterations to soil structure would be expected to change the rates of many microbial processes, including those in the nitrogen cycle. An example is denitrification, a process that occurs anaerobically, within the center of soil aggregates, which reduces nitrate and nitrite to gaseous forms of nitrogen, including nitrous oxide and nitrogen. Effects on emissions of nitrous oxide and other important greenhouse gases are only now being examined (*12*). One study (*10*) found an increase in arbuscular mycorrhizal fungi, a key symbiont group that associates with plant roots. If generally true, this could affect phosphorus cycling, because these symbionts transport nutrients, including phosphorus, to their plant hosts.

Plastic films, and likely fibers, may alter the flow of water in soils, including evaporation (*13*). Thus, effects on ecosystem water dynamics and energy balance, mediated by direct effects in soils or indirectly through plants, are also likely. Other possible ecosystem-level effects include altered rates of erosion owing to changes in soil aggregate stability.

There are some critical unknowns that need to be addressed before the impacts of microplastic pollution on terrestrial ecosystems and the subsequent feedbacks can be understood. Accurate, sensitive, low-cost, and harmonized detection methods and high-throughput sample processing are needed (*14*), to better understand the effects on turnover and transformation processes in the soil. Beyond this, research needs to cover more ecosystem types. Most research has so far focused on agricultural systems, which are expected to contain the largest amount of microplastics (*15*) because of input pathways (including sewage sludge, compost, and plastic mulching). We know much less about microplastics in other ecosystems, such as drylands or forests, where the microplastic dynamics might be quite different because of the different ecosystem structures.

Feedbacks to the Earth system can be expected. Microplastic itself represents fossil carbon, which might indirectly affect rates of net primary production and carbon storage in soils and alter the fluxes of greenhouse gases. The direction, magnitude, and balance of these effects should be a focus of future research. Empirical work will need to adopt tools such as mesocosm studies (outdoor experimental systems that examine the natural environment under controlled conditions) and carefully designed field experiments to address these problems. Microplastic pollution is an international problem, and international cooperation in research will be key. ■

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